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Recommendations for the Development of a Dust Suppressant Test Operations Procedure (TOP) Performed at the U.S. Army Yuma Proving Ground

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Desert Research Institute,
Division of Earth & Ecosystem Sciences

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14. ABSTRACT

Suppression of airborne dust is of critical importance in desert military operating environments. Airborne dust is commonly generated in the desert by surface and near-surface operations through a variety of different traffic impacts. The U.S. Army currently lacks a specific Test Operations Procedure (TOP) designed to provide realistic testing of the performance and durability of commercial products sold for dust abatement. The purpose of this study was to provide recommendations for the development of a TOP through implementing test designs and test procedures involving a polyvinyl-based synthetic polymer dust suppressant application. The methodology and design, as well as geotechnical surface strength and direct dust emissions testing were conducted on six different traffic impact types at three test sites at YPG. The test site locations represent a variety of soils texture types and site preparations methods. The traffic impacts included multiple passes by wheeled and tracked vehicles, rotary aircraft, and pedestrian traffic. The dust suppressant testing was conducted at 4 time intervals over the course of 5 to 6 days, spanning a period of 19 weeks.

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EXECUTIVE SUMMARY

Introduction

Suppression of airborne dust is of critical importance in desert military operating environments. Airborne dust is commonly generated in the desert by surface and near-surface operations through a variety of different traffic impacts. The U.S. Army currently lacks a specific Test Operations Procedure (TOP) designed to provide realistic testing of commercial products sold for dust abatement. The Desert Research Institute (DRI) was contracted by the U.S. Army Yuma Proving Ground (YPG) Natural Environments Test Office (NETO) to provide recommendations for the development of a TOP through implementing test designs and test procedures for evaluating dust suppressant performance and durability.

This document presents the methodology and design, as well as the results of tests conducted using a single dust suppressant product subjected to six different traffic impact types at three test sites in YPG over a period of 19 weeks in support of the development of a TOP. The product used in this study (TerraLOC®) is both water soluble and biodegradable. Test sites were located at the following locations: Muggins Mesa Dust Course (MMDC), Sidewinder Drop Zone (SDZ), and La Posa Drop Zone (LPDZ). The test site locations represent a variety of soil texture types and site preparation methods. The traffic impacts included multiple passes by the following vehicles: (1) a fully-tracked light armored personnel carrier vehicle (APC M113), (2) a medium armored, eight-wheeled, all-wheel-drive combat vehicle (STRYKER ESV M1132), (3) a medium, tactical, four-wheeled standard cargo truck (FMTV M1078), (4) a light, tactical, four-wheeled high mobility multipurpose wheeled vehicle (HMMWV M998), (5) a multipurpose utility helicopter (Bell UH-1), and (6) pedestrian (i.e., foot) traffic. The dust suppressant testing was conducted at 4 time intervals of 5 to 6 days in duration that spanned a period of 19 weeks from early May to September 2008.

Conclusions and Recommendations

The primary objective of this study is to provide recommendations and guidelines to support future development of a TOP for testing soil suppressants for military operations. The following recommendations are based on the results from testing one dust suppressant for this study and may not apply to all dust suppressants subjected to future testing. The results here may generally apply only to soils in desert regions, although most of the test methods (instrumentation, plot layouts) may be suitable for testing in other soil-climatic

regimes. Based on the results and discussion presented in the following sections, recommendations are presented as follows:

<u>Development of test parameters for testing soil suppressants for dust abatement</u>:

- Test procedures used in this study were focused only on testing soil suppressant performance on dust abatement. Additional uses of soil suppressants, such as for erosion control, will likely require a different test design and set of procedures.
- Development of TOP criteria to determine specific performance and durability parameters of soil suppressants for dust abatement are required. Criteria to define performance (ability to limit dust emission from dust-rich soils) and durability (time interval over which a pre-determined level of performance is maintained) are required to develop meaningful TOPs. Determination of specific parameters should be based upon established mission requirements for dust abatement.
- Performance in this study was defined as a significant decrease in soil surface strength or a significant increase in dust emission following a specific type of traffic impact. Other approaches that may be more useful for setting performance levels may include setting a minimum level of performance as being surface strength values that are 50% or higher and dust emission values that are 50% or lower than the mean values between the applied soil suppressant (static baseline) and a disturbed soil with no applied suppressant (disturbed baseline).
- Durability in this study was measured as suppressant performance over a 133 day test period (i.e., applied suppressant was exposed to unmodified environmental conditions over 133 days). Testing for suppressant durability could be based on predetermined performance requirements for a suppressant. For example, military operations may require that the suppressant provide adequate dust abatement for 180 days, requiring that the TOP evaluates durability for at least 180 days of exposure.
- Three soil types used in this study provide reasonable analogs for soils in regions commonly engaged by current military activities in deserts in southwest Asia and the southwest U.S. that have a high potential for dust emission. Consideration of different study sites, representing different soil types, may provide additional information on the impacts of ground-based traffic. The soils used in this study were selected based on relatively high fractions of fine sand, silt, and clay that are typical of relatively flat desert terrain occupied on a large-scale by U.S. military forces. Soils with lower silt and higher sand or gravel contents, typical of many unimproved roads in desert regions, might be more appropriate for the testing of some types of suppressants for reducing dust emission related to traffic on dirt and gravel roads.

Use of control plots to evaluate suppressant performance and durability

- Control plots provide different types of data that may be necessary for monitoring and evaluating suppressant performance and durability criteria.
- A disturbed baseline plot provides a measure of maximum potential for dust emission and provides the best data to directly evaluate soil suppressant performance. Measurement of the disturbed baseline at each time interval provides a measure of any changes in dust emissivity and surface strength that might have occurred over the time period of testing. This parameter will vary over the test interval if environmental conditions change considerably (especially when soil moisture and relative humidity are variable).
- A static baseline control plot provides a metric for natural recovery of the surface over the test interval (capability for a decrease in dust emission over time due to formation of a natural soil crust). Natural recovery may result in a systematic decrease in dust emission over time, resulting in a decrease in dust emission levels that is nearly equal to that of the applied soil suppressant. This natural recovery may mask or overshadow concomitant changes in soil suppressant dust abatement. Use of static baseline plots may be critical in the evaluation of durability over time intervals >100 days.
- A static benchline control plot provides a direct measure of soil suppressant durability by providing a direct measure of surface strength and dust emission at different time intervals over the test period.
- Of note, the disturbed baseline plot data could be partially replaced with data from measurements made at T=0 on the static baseline plots to reduce time and resources for data collection, or if significant changes in environmental conditions are experienced.
- The design of the three control plots can be used alone to test the durability performance of soil suppressants for TOPs where no physical impact to the suppressant from military equipment or personnel is expected.

Types of traffic impacts used in evaluating suppressant performance

- The combination of traffic impact plots and the instrumentation used in this study demonstrates that determining suppressant performance and durability can be readily established.

- Testing of ground-based traffic impacts may not require multiple vehicle types. The use of only a single wheeled vehicle, perhaps supplemented with a heavy-tracked vehicle, will provide adequate data for evaluating performance and durability requirements.
- The number of passes (vehicular, foot) for testing ground-based traffic impacts requires consideration of desired performance and durability standards.
- The methods used in this study may not adequately test the actual impact of rotorcraft on soil suppressant that will occur during landing and takeoff or that is associated with ground-based support. Any physical disruption to the suppressant from vehicle, foot, or aircraft contact with the soil suppressant will likely result in degradation or damage by the rotorwash that may compromise the integrity of the suppressant. Development of TOPs for evaluation of soil suppressants in areas of aircraft operation may require additional testing to determine performance and durability in areas where physical disruption of the suppressant is likely to occur in addition to rotorwash.

<u>Instrumentation and methods used in testing performance and durability</u>

- The soil testing instruments used in this study, including the pocket penetrometer, pocket vane shear tester, and the PI-SWERL (Portable *In Situ* Wind ERosion Laboratory), provided excellent data to quantitatively evaluate the performance and durability of the suppressant.
- Other instrumentation, such as a cone penetrometer and nuclear density gauge, would be useful for characterizing the soil prior to testing, to better assess differences in potential bearing capacity and subsurface soil strength. This would provide useful information to evaluate the overall trafficability of the soil surface, which in turn could be used to assess the performance of the strength of the suppressant during traffic impact testing.
- PI-SWERL provided an efficient and portable method to quantify dust emission on different surfaces as a function of traffic type, disturbance, and suppressant. Previous studies of soil suppressant performance have largely relied upon subjective observational data or have used passive measures such as dust traps to measure emitted dust. Although PI-SWERL is cost-effective relative to a wind tunnel, limitations for the use of PI-SWERL include the high cost of the instrumentation and an understanding that operation of the instrumentation requires specialized knowledge of soils and substantial instrument training.

- Crust thickness should not be used as a proxy for surface strength properties, but can be used to determine if the application of suppressant was conducted evenly across the test plots.
- Visual assessment and photographic documentation appear to be useful metrics for time-dependent changes of the suppressant crust after impact, as well as to relay information by a more qualitative, observational method.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Suppression of airborne dust is of critical importance in desert military operating environments. Airborne dust is commonly generated in the desert by surface and near-surface operations through a variety of different traffic impacts. The U.S. Army currently lacks a specific Test Operations Procedure (TOP) designed to provide realistic testing of the performance and durability of commercial products sold for dust abatement. The Desert Research Institute (DRI) was contracted by the U.S. Army Yuma Proving Ground (YPG) Natural Environments Test Office (NETO) to provide recommendations for the development of a TOP through implementing test designs and test procedures involving a polyvinyl-based synthetic polymer dust suppressant application.

This document presents the methodology and design, as well as the results of tests conducted using a polyvinyl-based synthetic polymer dust suppressant product subjected to six different traffic impact types at three test sites in YPG over a period of 19 weeks in support of the development of a TOP. Test sites were located at the following locations: Muggins Mesa Dust Course (MMDC), Sidewinder Drop Zone (SDZ), and La Posa Drop Zone (LPDZ). The test site locations represent a variety of soil texture types and site preparation methods. The traffic impacts included multiple passes by the following vehicles: (1) a full-tracked light armored personnel carrier vehicle (APC M113), (2) a medium armored, eight-wheeled, all-wheel-drive combat vehicle (STRYKER ESV M1132), (3) a medium, tactical, four-wheeled standard cargo truck (FMTV M1078), (4) a light, tactical, four-wheeled high mobility multipurpose wheeled vehicle (HMMWV M998), (5) a multipurpose utility helicopter (Bell UH-1), and (6) pedestrian (i.e., foot) traffic. The dust suppressant testing was conducted at 4 time intervals of 5 to 6 days in duration that spanned a period of 19 weeks from early May to September 2008.

The remainder of this chapter (Chapter 1) outlines the background of dust suppression studies for military operating environments in general, the purpose of this study in particular, basic physiography and climate characteristics for the study area, and test site descriptions. A brief discussion of surface factors that control dust emission is also included in the review of dust suppression studies. Chapter 2 provides information on test design and layout, and the methods employed, including field and laboratory testing. Chapter 3 includes a discussion of environmental conditions during the testing, a discussion of the results, and provides an evaluation of the study design and testing methods. The results presented in this study are based on testing of surface strength characteristics (shear strength and penetration

resistance), dust emission measurements using a Portable *In Situ* Wind ERosion Laboratory (PI-SWERL [Etyemezian et al., 2007; Sweeney et al., 2008]), soil sampling and laboratory analysis, and semi-quantitative visual observation. Chapter 4 concludes the report with a summary discussion and recommendations concerning the future development of a dust suppressant TOP.

1.1 Dust Suppressant Studies

1.1.1 Dust suppressant tests for military applications

The need for suppression of airborne dust in desert military operating environments has led to multiple studies. The variety of previous tests on dust suppression materials indicates the need for a standardized testing procedure. The following review of dust suppression testing is not meant to be exhaustive, but rather to broadly familiarize the reader with previous testing designs and methods.

Previous dust emission test designs have examined airborne dust generation as a result of different traffic impact types, including rotorcraft (Orts et al., 2007; Tingle et al., 2004) and wheeled vehicles (Rushing et al., 2005; 2006) over a defined time period. Time periods for testing designs range from 30 to 220 days after application of the suppressant, with a series of tests usually performed over shorter time intervals to evaluate performance over time. Test surfaces generally vary based on the type of traffic impact: existing unpaved roadways for wheeled vehicles and open desert with sparse vegetation for rotorcraft. Testing designs usually incorporate some sort of control plot for comparative purposes, where a test surface has been subjected to a water treatment or lacks a dust suppressant application (Belnap et al., 2007).

Previous testing methods include measurements of airborne and redeposited dust after disturbance by a particular traffic impact type. Both qualitative and quantitative measurements have been used, in part due to the inherent difficulty of quantitatively measuring the amount of airborne dust produced during a test. Qualitative or semi-qualitative methods generally consist of visual estimations of airborne dust generation. Quantitative analyses include strength measurements of the application surface with a variety of instruments such as a dynamic cone penetrometer, and dust collection through both passive settling into collectors and active airborne dust filtration using an electric vacuum. With respect to test surface characterization, further quantitative methods involve categorizing the test surfaces according to the Unified Soils Classification System (USCS

[per ASTM, 2000a,b]), characterizing their bulk density and moisture properties using a nuclear density gauge, as well as measuring the application crust thickness. Test surfaces have also been described using semi-quantitative visual estimations of surface integrity. The methods used in the previous dust emission studies reviewed in this section are shown in Table 1.

1.1.2 Factors influencing dust emission potential

Surface characteristics are important factors influencing wind driven dust emissions. Three of the most important factors are soil moisture, surface roughness, and crusting. Soil moisture can increase the threshold friction velocity of a soil (Chepil, 1956; Saleh and Fryrear, 1995). McKenna Neuman and Nickling (1989) showed that the particles are held together by the capillary effect of soil moisture. Moisture content of 4% (kg H_2O/kg soil mass) is usually sufficient to cause cessation of particle entrainment, thereby shutting down the transport system (Bisal and Hsieh, 1966). Gillette (1999) has observed that wind erosion can follow as quickly as 10-30 minutes following a soaking rainstorm and suggests the reason for such a short time to return to erosion conditions is that the eroding layer need only be about a millimeter thick. Depending on soil texture, the time required to dry such a thin layer in high wind conditions can be fairly short. Effects of moisture exert influence over a longer time frame through surface crust development and aggregate formation, as well as creating conditions more conducive to vegetation growth that acts to protect the surface.

In addition to the wind friction velocity, which is the driving mechanism for dust emission through the saltation of larger particles, soil aerodynamic roughness (z_o) is also an important parameter. This property of the surface is related to its physical roughness and conditions the threshold above which saltation and sandblasting can occur. According to Gillette (1999), surfaces that have z_o greater than 1 mm are not likely to emit dust under any but the most severe winds. Logie (1982) demonstrated that low densities of roughness elements – pebbles and glass spheres placed on sand surfaces – actually lower the threshold friction velocity (u_{*t}, the friction velocity at which wind erosion is initiated) by promoting local flow acceleration and scouring. High densities of roughness elements raise u_{*t} due to increased surface protection and absorption of momentum from the wind (Logie, 1982; McKenna Neuman and Nickling, 1989; Gillies et al., 2000; Crawley and Nickling, 2003). At higher densities, non-erodible surface roughness (solid elements or porous vegetation) acts to increase u_{*t} above values found for smooth surfaces (Gillette, 1999). This is due to two effects: 1) non-erodible roughness elements directly cover part of the surface, and 2) they

absorb part of the wind momentum that would have been available to initiate particle motion and then subsequently transport the sediment. This momentum partitioning leads to a decrease of shear stress acting on the erodible surface and consequently the erosion efficiency.

The other property of the surface that has an influence on dust production is the dry size distribution of the soil aggregates present in the loose, wind-erodible fraction of the soil. According to Alfaro et al. (2004), the aptitude of a soil to emit dust is conditioned to a large extent by the size (geometric mean diameter) of the finest soil-aggregate population it contains. Alfaro et al. (2004) demonstrated by using data from wind tunnel tests carried out by Nickling and Gillies (1989) that soils with a high potential for dust emission contained a fine soil aggregate population. The fact that these soils were characterized by quite different silt and clay contents shows that, contrary to what is often assumed, texture is not directly a relevant parameter to predict the aptitude of a soil for dust emission. Nonetheless, texture may play an indirect role because the crusts that form at the soil surface often limit saltation, and hence dust production, and are more likely to form on fine-grained soils than on coarse-grained ones.

The presence or absence of soil crusts can have considerable effect on the magnitude of dust emissions. The strength of bonding between the soil particles or aggregates affects the likelihood of individual particles being entrained by the local airflow. Even a weak crust has been shown to reduce the rate of erosion significantly (Gillette et al., 1982), protecting the underlying less cohesive particles from the forces of entrainment. Chepil (1953; 1958) suggested that the erosion rate of crusted soils may vary by a factor of 0.4 to 0.04 compared to that found for freshly disturbed (i.e., cultivated) soils. Zobeck (1991) found that some crusts may be much more effective at reducing erosion, with erosion rates reduced from 0.2 to 0.0002 as compared to an un-crusted surface.

1.2 Project Scope and Objectives

The primary purpose of this study is to provide recommendations for the future development of a TOP for testing dust suppressants. The recommendations provided by this study are based on experimental test designs and procedures implemented at YPG involving a single proprietary polyvinyl-based synthetic polymer dust suppressant application marketed commercially. Documentation of the test designs and procedures constitute a secondary purpose of this study. The results of this study are presented primarily as (1) a

series of images and graphs with summary text based on the testing results and (2) a list of recommendations for consideration in future development of a TOP.

Furthermore, the overall goal of this study was not to specifically test and evaluate the performance of the proprietor's soil suppressant, but rather to guide and make recommendations for the development of a TOP for future testing of soil suppressants. Therefore, the use of the particular product in this study should not be regarded as an endorsement of the soil suppressant.

1.3 Site Location and Description

1.3.1 Location of Yuma Proving Ground

YPG is a general-purpose testing facility within the U.S. Army Test and Evaluation Command (ATEC). The facility is located near the convergence of the Gila and Colorado Rivers in southwestern Arizona, near the border with California (Figure 1). The facility is approximately 25 mi (40 km) north of Yuma, Arizona. The YPG encompasses over 1,274 mi^2 (3,300 km^2) of the hottest and driest desert land in North America, with average day-time temperatures of 87.30° F (30.72° C) and mean annual rainfall of 2.91 in (74 mm) (Dunbier, 1968). In plan view, the facility is essentially U-shaped and extends 56 mi (90 km) in the north-south direction and 53 mi (85 km) in the east-west.

1.3.2 Physiography and Geology

YPG is situated in the northern Sonoran Desert, and extends across the lower Colorado River and Basin and Range physiographic regions. The region is dominated by north-south trending, sub-parallel mountain ranges separated by gently sloping alluvial basins. The intermontane basins are primarily composed of alluvial fans of variable ages and source materials, which typically transition into less steeply sloping alluvial plains and fan terraces. These geomorphic surfaces are commonly dissected and drained by ephemeral streams and are frequently armored by well-developed and darkly varnished desert pavement. Source areas for alluvial material within the study areas include the Castle Dome Mountains, Middle Mountains, and Muggins Mountains. The mountains generally consist of a variety of bedrock types including: igneous (basalt, granite, and rhyolite), metamorphic (schist and gneiss), and sedimentary rocks of Quaternary, Tertiary, and older age. Quaternary-age alluvial fans comprise nearly half of the surface area of YPG (McDonald et al., 2007).

1.3.3 Climate

Climate at YPG is characterized by extreme temperatures and low precipitation. Winters are short and generally mild, with an average daily temperature in December and January of 53.6°F (12°C). Yuma Proving Ground experiences very hot summers. The average daily temperature in July is 93.2°F (34°C) with maximum summer temperatures in excess of 122°F (50°C). The mean annual temperature and precipitation recorded from 1958 to 2006 (station 029654: <http://www.wrcc.dri.edu/climsum.html>) are 73.9°F (23.3°C) (daily maximum of 124°F (51.1°C)) and 3.7 in (95 mm), respectively. Annual precipitation largely occurs in the winter months from north Pacific frontal storms and during late summer months from monsoonal-type convective storms and infrequent dissipating tropical cyclones. The tropical storm influence can be either during the active phase (rare), or during decay stages (occasional), or by way of remnant moisture plumes from a distant demise (common). These causes are in turn modulated by larger-scale climate phenomena, particularly in the world's oceans, primarily the Pacific. Among these sources of variability are the El Niño and La Niña and perhaps the Pacific Decadal Oscillation climatic patterns centered in the eastern Pacific Ocean.

1.3.4 Study Site 1 - Muggins Mesa Dust Course (MMDC)

The MMDC is located approximately 7.6 mi (12.2 km) southeast of the Main Post (Figure 1). The test site portion of the course is situated on a late Pleistocene-age Qf2 alluvial fan landform (McDonald and Bacon 2006). The surface cover of this landform at the test site ranges from poorly-graded gravel with silt and sand [USCS symbol: GP-GM] to silty sand with gravel [SM (>15% gravel)]. Per the U.S. Department of Agriculture (USDA) soil classification system, the surface texture at the test site is a very gravelly loam to very gravelly silt loam.

1.3.5 Study Site 2 - Sidewinder Drop Zone (SDZ)

The SDZ is located about 5.4 mi (8.7 km) northeast of the Main Post (Figure 1). The test site portion of the drop zone is situated on a Qf2 alluvial fan landform that has been dissected by a Holocene-age Qf5 active wash landform (McDonald et al., 2007). The surface cover of these landforms at the test site ranges from very loose, gravelly silty sand [SM] to well-graded gravel with sand [GW]. Per the USDA classification system, the surface texture at the test site ranges from a very gravelly loam to very gravelly silt.

1.3.6 Study Site 3 - La Posa Drop Zone (LPDZ)

The LPDZ is located about 38 mi (61.2 km) north-northeast of the Main Post (Figure 1). The test site portion of the drop zone is situated on late Pleistocene- and Holocene-age Qp1 and Qp3a alluvial plain landforms, respectively (McDonald et al., 2008). The surface cover of the landforms at the test site is very soft, gravelly sandy silt [ML]. Per the USDA classification system, the surface texture is a gravelly silt loam.

2.0 STUDY DESIGN AND METHODS

2.1 Site Selection and Preparation

The test locations of MMDC, SDZ, and LPDZ were selected based on accessibility, differences in surface texture and overall soil characteristics, and are areas where the soil has been disrupted by previous military testing.

2.1.1 Site Preparation

The surface of each site was thoroughly mixed (to a depth of ~15 cm) through disking and subsequent dragging of a heavy linked-chain to eliminate furrows. In addition, MMDC was bladed to achieve additional surface compaction after the furrows were eliminated. MMDC was bladed because the soil cover and texture was similar to that of SDZ.

At each test site, the dust suppressant product was applied only once at the beginning of the 19 week testing period, 24 to 48 hours immediately prior to the onset of the testing. A time interval of 24 to 48 hours was specified by the suppressant manufacturer to provide sufficient time for the suppressant to properly cure. Each test site contains one or two test layouts (as described below in Section 2.2), wherein either ground-based or rotorcraft traffic impact types were tested. LPDZ is an exception, where rotorcraft and pedestrian traffic tests were combined in the same layout. The two test layouts at LPDZ were also subjected to different suppressant treatment formulations: a standard formulation (SF) identical to the other test layouts applied to the easternmost test layout, and a different formulation (DF) applied to the westernmost test layout.

2.1.2 Soil Suppressant Used in this Study

The soil suppressant used in this study was the TerraLOC® dust suppressant produced by MonoSol, LLC. The TerraLOC® Xtra formulation was applied to all test plots except for the DF layout at LPDZ, where the TerraLOC® Standard formulation was applied. Chemical dust suppressant formulations vary widely, to include salts, oils, fiber mixtures and synthetic polymers. All of the formulations work in some fashion to bind soil particles into bigger or heavier particles to prevent airborne emission. However, they vary in durability, water solubility, and the hazards associated with both product application and long term exposure in the environment. TerraLOC® is classed as a polyvinyl-based synthetic polymer. Information provided by MonoSol, LLC, indicates that TerraLOC is safe

for human health, has negligible impact to application equipment, and has environmentally benign characteristics of biodegradability and water solubility (Appendix A). Other types of dust suppressants tested in the future may require specific environmental clearances and safety standard operating procedures that were not required on this test. This suppressant was provided to YPG-NETO under a contract with MonoSol LLC.

MonoSol, LLC was responsible for the application of the dust suppressant. The dust suppressant for ground-based layouts was applied using a 4,000 gallon (15,142 liter) Kenworth water truck equipped with external Honda centrifugal pumps. The application for such layouts was done in 15 ft (4.6 m) swaths and in two separate passes. The dust suppressant for rotorcraft layouts was applied using a 1,000 gallon (3,785 liter) water trailer, equipped with a proprietary applicator and Honda centrifugal pumps. The water trailer was towed by a Massey Ferguson tractor. The application for rotorcraft traffic was done in 15 ft (4.6 m) swaths and in one pass. Table 2 lists the size of each test layout, and the amount of dust suppressant applied. Although the target dilution ratio of water to dust suppressant was 5:1 at MMDC and the ground-based traffic test plot at SWDZ, the actual dilution ratio ranged from 4.6:1 to 4.9:1. The target dilution ratio for the remaining test plots was 6:1, with an actual dilution ratio of 6.3:1.

2.2 Traffic Impact Test Design

The test design incorporated testing for a variety of traffic impact types at each of the three test sites at 4 test time intervals over a period of 19 weeks. Test time intervals, starting with T=0, occurred immediately after the application of the suppressant, including the 24 to 48 hours required for the curing of the dust suppressant (hereafter referred to as ‘the application’). The other three test intervals occurred at 35 days after application (T=35), 70 days after application (T=70), and 133 days after application (T=133). Precipitation events during the T=70 and T=133 test time intervals prevented testing during those times at the LPDZ test site.

Each test site contains one or two test layouts comprising a number of traffic test plots and 3 control plots (Figures 2 through 5). Ground-based and air-based traffic impact types were usually tested in separate layouts at test sites for logistical and safety reasons. The test layout boundaries were initially delineated using 3.3 ft (1 m) resolution IKONOS satellite imagery and the corners of each layout were then surveyed by a hand-held Global Positioning System (GPS) device and marked on the ground with 3.0 ft (0.9 m) long construction stakes and flagging

Previously untested traffic test plots were subject to repeated passes of a particular traffic impact type at each test time interval. As the sole exception, due to space constraints, the final rotorcraft testing during T=133 occurred on previously impacted (rotorcraft) traffic test plots. Testing (i.e field measurement) was conducted after a specific number of cumulative passes, hereafter referred to as the test pass interval, as explained in Section 2.2.2, below. Design elements aimed to minimize potential dust cross-contamination included: (1) properly sizing the traffic test plots (described below), (2) orienting traffic test plots relative to the direction of the prevailing wind such that subsequent tests would likely remain upwind, and (3) ensuring sufficient space outside of the test plots for traffic to maneuver, especially in the course of looping back for multiple passes, in an upwind direction.

2.2.1 Traffic Impact Types

The types of traffic impacts tested consisted of 1 tracked vehicle, 3 wheeled vehicles of various weights, pedestrian traffic, and rotorcraft. Table 3 lists the weight of each traffic impact type and the site at which it was tested for this study.

2.2.2 Traffic Test Plots

Traffic test plots for ground-based vehicles measured 26 ft (7.9 m) by 100 ft (30.5 m). Pedestrian traffic test plots also measured 26 ft (7.9 m) by 100 ft (30.5 m) when adjacent to ground-based vehicle testing, and measured 10 ft (3.0 m) by 100 ft (30.5 m) next to rotorcraft test plots. Rotorcraft test plots measured 150 ft (45.7 m) by 200 ft (61.0 m). The bounding corners of individual traffic impact plots were determined using a 328 ft (100 m) long tape relative to staked corners of the test layout and then marked with 3.0 ft (0.9 m) long construction stakes and flagging. Each traffic test plot was divided into 4 equal sections along the long axis. Testing occurred in a different section during each test pass interval to assure that testing occurred on a previously untested portion of the impacted area of traffic test plots. The initial pass for ground-based vehicles was centered along the long axis of the traffic test plot. All subsequent passes traversed the plot in the same direction and were carefully lined up and guided by project personnel to maintain the same trajectory and zone of impact (i.e., tire or tread tracks). Pedestrian traffic was guided by the placement of a 328 ft (100 m) long tape on the ground that ran along the center of the traffic test plot to maintain the same trajectory and zone of impact as previous passes. Painted sand bags were placed along the long axis in the center of rotorcraft test plots for reference to achieve a straight flight line.

Surface testing at the vehicle and pedestrian traffic test plots took place within the area where the suppressant was clearly disturbed. Surface testing at the rotorcraft test plots occurred within the area of maximum shear stress for the Bell UH-1 helicopter, modeled to occur at a distance of 23 to 33 ft (7.0 to 10.0 m) perpendicular to the centerline of travel on the starboard side of the rotorcraft (McAlpine, 2009). Surface testing at traffic test plots began after a specific number of vehicle/rotorcraft-specific passes had elapsed. These were made at multiples of 5 passes for ground-based vehicles, 10 passes for rotorcraft, and 40 passes for pedestrian traffic. The specific number of passes was determined in the field after visually assessing the integrity of the dust suppressant. Table 3 presents the test pass intervals of each traffic type. Surface tests and procedures performed at each test pass interval are described below in Section 2.3.

2.2.3 Control Plots

The control plots measured 50 ft (15.2 m) by 100 ft (30.5 m), except for one control plot each at the SDZ rotorcraft layout and the LPDZ (DF) test layout, which both measured 50 ft (15.2 m) by 200 ft (61.0 m) (Figure 4). The bounding corners of control plots were determined using a 328 ft (100 m) long tape measuring from the corners of the test layout and marked with 3.0 ft (0.9 m) long construction stakes and flagging. Each control plot was divided into 4 grid sections along the long axis, where testing occurred in a different grid section during each test time interval to assure that testing occurred on a previously untested surface, as well as to maintain surface integrity and lack of disturbance through the entire test period.

Three types of control plots were incorporated into each test layout: disturbed baseline, static baseline, and static benchline. The disturbed baseline control plots were not subject to the application, and were manually disturbed through hand raking down to a depth of ~3.0 in (~7.6 cm) immediately before testing at each test time interval. The static baseline control plots were not subject to the application, and also were not subjected to any subsequent anthropogenic impacts. The purpose of the static baseline and disturbed baseline control plots was to provide data from surfaces subjected to the same atmospheric conditions as the application test plots. As such, the static baseline control plot was designed to provide a measurement of natural soil settling and surface crust formation over time, while the disturbed baseline control plot was designed to provide a measurement of the constant impact on a surface lacking the application. These control surfaces are needed to assess the incremental durability of the application. The static benchline control plots included the application, but were not subjected to any subsequent impacts. The purpose of testing the

static benchline control plot is to provide data for surface characteristics of other unimpacted application surfaces, such as traffic test plots immediately before being impacted by a particular traffic type.

All control plots were tested at each test time interval, except for the previously noted precipitation events at LPDZ during T=70 and T=133, and except for the static baseline and disturbed baseline control plots at the LPDZ (SF and DF) test layouts. Surface conditions at these two control plots were assumed to be similar to their counterparts at the LPDZ (DF) test layout. Control plots were tested at each test time interval to assess the incremental durability of the application over time. The testing methods and procedures conducted at control and traffic impact plots are described in the following sections.

2.3 Traffic Impact Testing Methods

Both quantitative and semi-qualitative methods were employed to characterize surfaces at control and traffic impact plots. The methods selected for this study are techniques that provide a balance between providing quantification of soil surface condition and the application's performance, as well as ease of application and cost.

2.3.1 Surface Properties

Surface testing was conducted on traffic test plots at the conclusion of each test pass interval and on control plots at each test time interval. Control plots and traffic test plots were examined and described using standard soil and geotechnical techniques (Schoeneberger et al. 2002; ASTM, 2000a,b; Soil Survey Staff, 1995). Two geotechnical properties were measured at control plots and impacted areas of traffic impact plots: penetration resistance and surface shear strength. Penetration resistance was measured using an E-284 dial type pocket penetrometer (GeoTest Instrument Corp.), and surface shear strength was measured using an E-285 pocket vane shear tester (GeoTest Instrument Corp.). The use of these instruments provides a direct measure of the application crust strength and not the untreated subsoils because of the small area and depth that is measured. The pocket penetrometer effectively measures only the uppermost 0.4-0.8 in (1.0-2.0 cm) depth of the soil and the shear vane only about 0.8-1.6 in (2.0-4.1 cm) diameter and ~0.4 in (1 cm) depth. By comparison, a traditional cone-penetrometer used by soil scientists for agricultural purposes more effectively measures penetration resistance to depths well in excess of the relatively thin coatings produced by most soil suppressants.

The thickness of the crust formed by the application was also measured at each test time interval. In static benchline control plots, crust thickness was measured by sampling along the same long axis of other data gathering activities for that same test time interval. In non-impacted areas of traffic test plots, crust thickness was measured by sampling adjacent to and parallel with the axis of vehicle tracks.

All surfaces at control and traffic test plots were photographed and assigned a numerical percentage of dust suppressant integrity based on visual assessment. Photographs were also taken to document an overview of the test plot and to show detailed views of the soil surface (Appendix E). The locations of the soil surface photographs were marked with an orange pin flag so as to facilitate repeat photographs of the same surface location over multiple test pass intervals (traffic test plots) or test time intervals (control plots) to document any change.

In addition to the geotechnical testing instruments used to measure the strength of the application, direct surface measurements of dust emission at the control and traffic test plots were made using a novel device – the Portable *In Situ* Wind ERosion Laboratory (PI-SWERL) of Etyemezian et al. (2007; United States Patent No. US 7,155,966 B1). Recently, a miniature version of the PI-SWERL has been developed that is mounted on an off-road carriage to further facilitate portability across difficult terrain. The PI-SWERL directly measures the emissions of dust at varying shear stresses, instead of attempting to simulate the atmospheric boundary layer. The PI-SWERL utilizes a 12-volt DC motor which sits on top of an open-bottomed cylindrical chamber. The motor is coupled to an annular ring, which hangs parallel to and several centimeters above the soil surface within the chamber. As the annular ring revolves around its center axis, according to a prescribed cycle (RPM) that is controlled by a computer, a velocity gradient is created between the flat portion of the ring (the outer 5 cm) and the ground. This results in the generation of wind shear close to the ground, similar to the effect of moving two parallel flat plates relative to one another. The magnitude of the shear stress increases with the rate of revolution and generates a friction velocity (u* m/s). The shear forces induced by the PI-SWERL causes soil particles to move along the ground surface via saltation, causing the smaller particles in the PM10 (particulate matter less than 10 microns) size fraction to be dislodged and emitted as dust. The concentration (mg/cm^3) of PM10 is monitored by a fast response instrument (DustTrak, TSI, Model 8520) which is attached to the top of the chamber using conductive tubing. The PI-SWERL provides an index of erodibility, through the ratio of the RPM to PM10 concentration, which can be used to compare the relative dust emission (mg/m^2s) at an associated friction velocity of two or more test areas. This type of measurement is similar to

those performed with considerably larger, straight wind tunnels (Gillies et al., 2005; Sweeney et al., 2008). The PI-SWERL does not provide for a realistic analog to rotorwash from rotorcraft traffic.

2.3.2 Soil Laboratory Analyses

All soil sampled for this project was analyzed at the DRI Soil Characterization and Quaternary Pedology Laboratory, Reno, Nevada. A representative soil sample was collected from control plots at each test time interval and from traffic impact plots after the final test pass interval for that plot. The following two laboratory analyses were performed on the soil samples from control plots: 1) particle size distribution (PSD) using the laser light scattering method (Gee and Or, 2002) and 2) bulk density per the clod and excavation of relatively in situ samples (Grossmann and Reinsch, 2002). Soil samples collected from the impacted areas of traffic impact plots were subjected to particle size distribution analysis only.

3.0 RESULTS AND DISCUSSION

The primary objective of this project is to provide recommendations for the establishment of a TOP for future testing of dust suppressants for application to military operations. The following section provides both results and discussion related to three main components of the test conducted in this study. These components are: (1) report the environmental conditions at the time of the test in relation to collected data and test results, (2) evaluate components of the test design (plot layout, impact type, frequency of measurement), and (3) assess techniques used to quantify suppressant performance and soil conditions.

The terms performance and durability will be used to evaluate the results of this study. Performance is related to the ability of a suppressant to limit dust emission relative to a soil that lacks a soil suppressant. Durability refers to the how long a soil suppressant maintains a specified level of performance. Performance for this project is judged as a significant or considerable decrease in either limiting dust emission and/or soil surface strength relative to the control plots. We emphasize again that discussion of performance and durability refers in principal to the testing of a generic soil suppressant and not specifically to the single commercial product used in this project.

3.1 Overview of Test Results and Conditions During Test Intervals

3.1.1 Overview of Test Data Collection

Field testing occurred over a period of 133 days in 2008 and at four time intervals: 28 April-03 May (T=0); 02-06 June (T=35); 08-10 July (T=70); and 09-11 September (T=133). Precipitation events at LPDZ on 09-11 July and 11 September prevented testing at that location during the latter two test time intervals (see 3.1.2 below). In general, 12 surface shear strength and 12 penetration resistance measurements were conducted at the end of each test pass interval for every traffic test plot and at each test time interval for every control plot. Over the four test time intervals at the three sites, about 1,920 measurements each of surface shear strength and penetration resistance were taken, divided among 126 total test pass intervals and 44 control plot tests. In cases where the instrument's measuring capability was exceeded, the maximum value was recorded. Over the four test time intervals at the three study sites, 803 total PI-SWERL tests were conducted, divided among the same number of test pass intervals and control plot tests. In sum, 87 soil samples were collected

and analyzed from the three study sites. Data collected from measurements and scanned images of original field forms are presented in Appendices C and D, respectively.

3.1.2 Meteorology During Test Interval

The sections below describe meteorological conditions at or near each test site over the testing period. Appendix B contains graphs of meteorological variables for each test site over the testing period. Meteorological data for MMDC and LPDZ were measured at the nearest available station and should be regarded as proxy data as described below. Meteorological data for SDZ was measured at the site.

Proxy meteorological data for MMDC were obtained from the YPG Kofa Dust station (http://www.wrcc.dri.edu/ypg/), located at a similar elevation about 2.2 mi (3.5 km) to the north-northeast. Over the testing period, temperatures ranged from a low of 56.1° F (13.4° C) in late May to a high of 111.7° F (44.3° C) in early August. Data from June to early July are unavailable. Relative humidity ranged from 1% at the end of May to 90% in late May. Six days of measureable precipitation were recorded for a total of .9 in (22.9 mm), with the highest daily amount of .4 in (10.4 mm) falling in early August. No measureable precipitation occurred within a week preceding testing at each test time interval at MMDC. Winds were primarily out of the southwest.

Meteorological data for SDZ were obtained from the YPG SDZ station (http://www.wrcc.dri.edu/ypg/), located at the study site. Over the testing period, temperatures ranged from a low of 50.4° F (10.2° C) in late May to a high of 115.9° F (46.6° C) in mid June. Relative humidity ranged from 3% in mid June to 88% in late May. No measureable precipitation was recorded during the test period. Winds were primarily out of the southwest.

Proxy meteorological data for LPDZ were obtained from the YPG Tyson Drop Zone station (http://www.wrcc.dri.edu/ypg/), located about 164 ft (50 m) higher in elevation and about 3.7 mi (6.0 km) to the south-southeast. Over the testing period, temperatures ranged from a low of 56.1° F (13.4° C) in late May to a high of 111.2° F (44.0° C) in late June. Relative humidity ranged from 2% in late June to 94% in late May. Nine days of measureable precipitation were recorded for a total of 1.7 in (43.7 mm), with the highest daily amount of 0.6 in (16.3 mm) falling in early September. As noted previously, the precipitation events recorded on 09-11 July and 11 September prevented testing at LPDZ. Winds were primarily out of the southwest.

3.1.3 Soil Texture, Moisture and Bulk Density

Appendix C presents graphs showing soil texture, moisture, and bulk density. All 87 soil samples collected over the four test time intervals were analyzed for soil texture and moisture. Soil texture of test layouts ranged from loam to silty-loam to silt. Soil moisture data were divided into samples that had been treated with the application and those that were untreated. Soil moisture of samples ranged from 0.4% to 2.6% for untreated samples and from 0.1% to 2.8% for treated samples. With few exceptions, the general trend shown on the soil moisture graphs is a decreasing soil moisture through time at all test sites. Differences in soil moisture between untreated and treated soil samples exceed 1σ standard deviation at two test time intervals at MMDC and one test time interval at LPDZ.

A subset of 51 soil samples with no suppressant application was collected from control plots and rotorcraft traffic impact plots for bulk density. Soil samples from ground-based traffic test plots were not analyzed for bulk density. Bulk density was generally lower at the finer-grained LPDZ site, ranging from about 1.2 g/cm^3 to 1.5 g/cm^3, whereas bulk density at the coarse-grained MMDC site was generally higher ranging from an outlier value of 1.2 g/cm^3 to 2.1 g/cm^3.

3.2 Evaluation of Test Design and Data Collection Methods

3.2.1 Use of Control Plots in Test Design

Three types of control plots were incorporated into each test layout (static benchline, static baseline, and disturbed baseline) to monitor changes in soil and suppressant conditions over specific test intervals. Each of the control plots provided information that can be potentially used to evaluate a suppressant's performance and durability. Overall the three control plot types displayed similar trends in surface conditions at each of the study sites. Different control plot types, however, do reveal important time-related changes in shear strength, penetration resistance, and PM10 dust emission at all sites over the duration of this study.

<u>Disturbed Baseline:</u> The disturbed baseline control plots were not subject to the application and were manually disturbed by hand raking at each test time interval immediately before testing. The purpose of testing the control plots was to provide data from surfaces subjected to the same atmospheric conditions as the test plots with the suppressant application. Mean shear strength and penetration resistance values increased at all control plots between T=0 and T= 35. This increase may reflect variation in soil moisture content, relative humidity,

and temperature that produce slight increases in soil strength or decreases in dust emissivity (Chepil, 1956; Gerard, 1965; McKenna Neuman and Nickling, 1989; Saleh and Fryrear, 1995). Mean shear strength and penetration resistance values generally decrease by T=133 and in many cases, return to values that are similar to values measured at T=0 (Figures 6 through 15). Dust emission values for the disturbed baseline control plots remained relatively constant from T=0 to T=133, but generally exhibit a slight decrease at T=70.

<u>Static Baseline:</u> The static baseline plots were subject to manual disturbance at T=0 as described above and were not treated with the application. No further disturbance of the soil surface occurred during the remainder of the test. These plots provide a measure of the soil's natural ability to stabilize, commonly by forming a surface crust. Surface strength and dust emission values were nearly similar at T=0 for both the disturbed baseline and static baseline plots (except for MMDC penetration resistance). Mean shear strength and penetration resistance values increase over time at all control plots between T=0 and T=133. Measured PM10 dust emission also decreases substantially between T=0 and T=133. In many cases surface strength and dust emission values at T=133 for the static baseline are nearly similar to values at T=133 for static benchline (plots where a soil suppressant was applied). These trends clearly demonstrate that the soil at each of the study sites developed a natural surface crust over time, thereby increasing in surface strength and stability. In other words, both the strength and dust emissivity of this natural crust return over time to nearly the same values as that of the static benchline plots that were subjected to the application (Figures 6 through 15).

<u>Static Benchline:</u> The static benchline control plots were subject to the dust suppressant application but were not subjected to any subsequent impacts after the initial site preparation prior to T=0. Surface strength and dust emissivity remained relatively constant for control plots at MMDC and SDZ sites through the test interval T=133. Data from control plots at the LPDZ site show an initial increase in surface strength, but data were not collected after T=35. The near constant trend in surface strength and dust emission values suggest in part that the application remained intact with limited degradation or changes in performance. The increase in surface strength and decrease in dust emissivity measured at the static baseline plots (no soil suppressant), however, also indicates that any possible degradation may be masked by the ability of the soil surface to naturally recover. In other words, the apparent stability of the application (static benchline plot trends) may actually result partially from the natural ability of the soil surface to form a stabilizing crust (static baseline plot trends) (Figures 6 through 15).

Evaluation of the three types of control plots suggest that they provide important information about changes in soil surface condition, especially when comparisons are made among plot types. For example, comparisons between trends in static benchline and static baseline control plots regarding the time frame required for natural soil crust development and concomitant dust suppression to approach that of a dust suppressant. This relationship has important implications for test design and goals in general, depending on whether testing is conducted to evaluate performance or durability. In evaluating performance, a static baseline control plot may be of limited utility unless there are considerable changes in environmental conditions or the test interval is conducted over multiple months. This is because large changes in soil moisture (i.e., related relative humidity and precipitation) might result in significant changes in surface strength and dust emissivity. In evaluating durability, a static baseline control plot allows for defining the amount of time required for natural undisturbed soils to produce surface strength and dust emission measurements similar to dust suppressant treated soils, increasing test efficiency by testing no longer than is necessary to establish such a relationship.

Additional test efficiencies may be created by eliminating potential redundancies in control plots depending on the required TOP. Test designs may optimize efficiency by testing the static baseline control plot in combination with either the static baseline or disturbed baseline control plots, but not both. In testing for performance, only static benchline and disturbed baseline control plots may require testing. In testing for durability, static benchline and static baseline control plots can be tested at each time interval, while the disturbed baseline may only be tested once for each study site at the start of testing (T=0) to establish the following: (1) the lowest possible surface strength values; and (2) the highest possible PM10 dust emission values. However, it may be prudent to test the disturbed baseline control plot subsequently in the event of changing environmental conditions (e.g., precipitation, increased humidity) that could potentially impact these properties. Finally, depending on the surface preparation of the study sites, the static baseline and disturbed baseline control plot conditions may be nearly identical (as was the case in the present study), permitting the testing of either, but not requiring both, at the onset of testing as an effective test efficiency measure.

3.2.2 Evaluation of the Three Study Sites

The three study sites, MMDC, SDZ, and LPDZ, were selected to provide a range of soil types typical of desert soils that might impact military operations. The surface cover of MMDC study site is generally a poorly-graded loose gravel with silt and sand [USCS

symbol: GP-GM], the surface cover of SDZ site is largely a very loose, gravelly silty-sand [SM], and the surface cover of LPDZ is a very soft, gravelly sandy-silt [ML]. The MMDC site is currently used as a vehicle-test course, whereas SDZ and LPDZ are sites where the surface soil has been deeply mixed by disking (>15 cm) to form a loose soil cover suitable for use as a drop zone for landing equipment via parachute. Values reported for surface strength and dust emission discussed above are generally similar in both range and magnitude. The primary reason for this similarity is that the soil texture among all test sites is generally comparable, especially with respect to a high silt content. It is important to note, however, that the data reported are based upon measurement of the <2 mm size fraction (i.e., exclusion of rock fragments >2 mm in diameter) and of a small volume of soil sampled at each site. Field observations indicate that the subsurface character and gravel content (>2mm size fraction) likely varies among each of the three sites. For example, LPDZ clearly is a 'softer soil' (low penetration resistance with depth) and less gravelly relative to both the SDZ and MMDC sites that contain more gravel and sand. These differences were not quantitatively measured as part of this investigation. Additional characterization of the soil, including the use of a cone-penetrometer and nuclear density gauge, would increase the characterization of the subsoil at each test course and for testing traffic impacts.

Differences among soil types may be important depending on the type of impact that is being evaluated, because other factors such as the competence of the subsoil and bearing capacity (for vehicles and foot traffic) will provide considerable control on a soil suppressant's performance and durability. Of the three study sites, for example, MMDC, which has been extensively used as a dust-test performance test course for ground-based traffic, is the closest approximation to an unimproved dirt road. The surface conditions at this test course, however, may not accurately reflect a high traffic-volume dirt or gravel compacted road such as a typical Military Supply Route (MSR). Other types of dirt or gravel roads or test courses at YPG may provide a more realistic test bed to simulate a MSR. LPDZ appears to provide a good analog for a soft soil with a high dust emission potential but may not be suitable for vehicle or foot traffic impact testing due to its limited bearing capacity.

The sites used in this study provide a good foundation in which to evaluate which soil types may be most beneficial in developing a potential TOP for testing soil suppressants. Additional consideration of the TOP requirements, especially an assessment of the type of performance required (i.e., ground-based vehicle traffic, rotorcraft impacts), will be necessary.

3.2.3 Evaluation of Wheeled and Tracked Vehicle Traffic Impact Tests

The test design used in this study employed multiple types of military traffic impacts, including multiple vehicles (wheeled and tracked), pedestrian traffic, and rotorcraft flyovers, to evaluate how different traffic types will impact soil suppressant performance. This information was collected in part to determine the most efficient methods to test a wide range of traffic types and across different soil types. This section includes a range of assessments including attention to (1) traffic test plot layouts, (2) vehicle types used to test traffic impacts to soil suppressants, and (3) the number of passes required to conduct a reasonable level of performance and durability testing. An assessment of the types of geotechnical measurements used to quantify soil surface conditions will be treated below in Section 3.3.1.

<u>Plot Design</u>: The compartmental plot design of vehicle impact test layout (Figures 2 through 5) proved very effective for conducting soil suppressant testing. The linear-rectangular layout provided adequate space to conduct all test procedures, and also facilitated application of the soil suppressant. The layout also provided ample space to maneuver all vehicles back into starting positions following each vehicle pass, as well as providing adequate space between each vehicle test lane to avoid any adverse impacts (dust cross-contamination, soil disturbance) to adjacent test lanes. The layout provided excellent visual communication between vehicle driver and ground support personnel for directing vehicles onto the correct lane position, while providing adequate space to conduct surface condition measurements concurrently on adjacent test lanes.

<u>Vehicle Type</u>: The results of the traffic tests generally indicate that the impact produced by different vehicle types did not differ substantially among the types tested. With the occasional exception of the two lightest vehicles (HMMWV and FMTV M1078) at MMDC, only 5 vehicle passes were required to produce significant suppressant degradation. Surface strength and dust emission data collected from MMDC and SDZ indicate that all four ground-based vehicles (HMMWV, M113, FMTV M1078, and STRYKER ESV) produced a considerable decrease in surface strength after only 5 passes at all time intervals. Likewise, there was considerable increase in dust emission after only 5 passes for all vehicles at all time intervals.

The overall similarity of results recorded by this study suggests that the type of vehicle may not be important in testing soil suppressant performance; however, only light-armored vehicles were used in this study. A heavy-armored tracked vehicle, such as the

M1A2 Abrahams main battle tank, is likely to produce a greater level of impact under these traffic test conditions (Berli et al., 2009).

<u>Number of Passes</u>: As stated in the section above, only 5 vehicle passes were required to produce a distinct and identifiable drop in surface strength and a significant increase in dust emission. This result is important because it demonstrates that performance of a soil suppressant in terms of traffic impacts can be readily established provided there are a sufficient number of vehicle passes. Development of a TOP for soil suppressants will require consideration of the number of passes that may be required to reach a failure point. The results of this study only apply to the test conditions used in this study because the number of passes required for this test will vary greatly depending on the strength of the soil suppressant, the soil type, subsoil properties, and the type of vehicle used during testing.

<u>Study Site and Soil Type</u>: Differences between MMDC and SDZ show the utility of testing traffic impacts on more than one soil type. Significant differences between MMDC and SDZ were evident in penetration resistance, shear strength, and PM10 dust emission. The differences between these sites are most likely related to the difference in study site preparation (blading at MMDC), differences in bulk density or gravel content, or a combination of properties, some of which may not have been measured in this study. Results also indicate that additional soil measurements would benefit the comparison between study sites, including characterization of each site using techniques such as cone-penetrometers (to measure subsurface soil strength) and a nuclear density gauge (to measure subsurface bulk density and moisture content). This additional information would enhance assessment of the soil's bearing capacity for vehicle traffic.

Overall evaluation of the vehicle traffic impact test results indicates that the test design used in this study is adequate for testing soil suppressant performance and durability for wheeled and tracked vehicular operations. First, the test layout provided a setting for easy management of vehicle traffic as well as excellent conditions for data collection. Second, the combination of the vehicles, the number of traffic test passes, and the field equipment employed provided data that could be used to adequately evaluate the performance and durability of the particular soil suppressant of this study. In other words, the test design provided a foundation in which to quantitatively evaluate the effectiveness of a given soil suppressant to withstand repeated impacts from vehicle traffic. Future development of a TOP should include consideration of heavily armored vehicles as an amendment to test design.

3.2.4 Evaluation of Pedestrian Traffic Impact Tests

Pedestrian (i.e., foot) traffic tests were designed to evaluate how to measure the impact of pedestrian traffic on soil suppressant performance and durability. A complete time series for pedestrian traffic was only available for test plots at the SDZ site because heavy precipitation at the LPDZ site eliminated measurements at T=70 and T=133.

Plot Design: The compartmental plot design was adequate for testing impacts related to pedestrian traffic in terms of access and adequate space to conduct measurements. The distance for each traffic impact traverse was 100 ft (30.5 m), which was the same as that used for vehicular traffic impacts (Figures 3 and 5). This test distance for pedestrian traffic could be shortened to about 24-30 ft (7.3-9.1 m) to save time, but still allow adequate space for measuring pedestrian traffic impacts.

Number of Passes: Surface strength decreased considerably after only 40 person passes for all time intervals at SDZ and after 40 or 80 person passes at LPDZ (Figures 31 and 33). Dust emission from pedestrian traffic increased considerably after 40 passes at the SDC site for all time intervals and showed a variable increase at the LPDZ site after 40 passes for the two time intervals (Figures 32 and 34). The results indicate that a point of suppressant performance failure (i.e., a substantial drop in either surface strength or and increase in dust emissivity) can be readily determined using this type of test design. Development of a TOP for testing pedestrian traffic impacts for soil suppressants requires consideration of the number of passes that may be required to reach a failure point.

Study Site and Soil Type: Minor differences in pedestrian traffic impacts occurred between the SDZ and LPDZ test sites although only two intervals can be compared. Pedestrian traffic impact on surface strength and dust emission was consistent at SDZ, resulting in recognizable trends, but was more variable at the LPDZ site.

Results of the pedestrian traffic tests indicate that soil suppressant performance and durability can be evaluated using the multiple pass interval approach as was conducted in this study. The number of passes required to demonstrate a decrease in soil suppressant effectiveness will vary with the type of suppressant used and the soil type.

3.2.5 Evaluation of Rotorcraft Impact Tests

The rotorcraft impact test was designed to evaluate potential rotorcraft impacts to soil suppressants during landing and takeoff operations. Safety concerns related to subjecting the aircraft to potentially hazardous brownout conditions prevented direct testing

of the suppressant through actual landings and takeoffs. Rotorcraft altitude was therefore maintained between 23 and 33 ft (7 and 10 m) above the ground surface with constant forward motion during the test.

Plot Design: The compartmental plot design was adequate for testing impacts related to rotorcraft flyovers in terms of access and safety, as well as providing adequate space to conduct measurements. Ideally, unless adequate space is not available (as at SDZ), rotorcraft traffic test plots for each time interval should be incorporated into the plot design.

Number of Passes: There were no obvious indicators for significant degradation of the suppressant between the interval of passes based on field observations and surface strength and dust emission measurements at SDZ and LPDZ (Figures 35 through 40). The surface strength measurements appear to reflect the relatively small natural variability of the strength of the suppressant independent of the application dilution. Variability in surface strength over repeated test pass intervals at different test time intervals may also be indicative of user and/or instrument error (e.g., Figure 35, T=0 and T=70). Also, the PM10 emission measurements typically show that the 0 pass (static benchline) emitted the most dust, likely because deposition of wind-blown dust between test time intervals cross-contaminated the test plots. All other pass intervals (10, 20, 30) had generally similar dust emission values. Development of a TOP for testing rotorcraft traffic for soil suppressants requires consideration of the number of passes that may be required to reach a failure point.

Study Site and Soil Type: Minor differences in rotorcraft impacts occurred at the SDZ and LPDZ test sites. Rotorcraft traffic impact on soil suppressant performance was consistent at SDZ, resulting in recognizable trends, but was more variable at the LPDZ site (Figures 35 through 40).

Results from surface strength measurements show minimal changes over the 133 day test period. There was a noticeable decrease in penetration resistance at T=35 at the SDZ and LPDZ sites. The PM10 dust emission data display a similar lack of observable trends between study sites and/or test layouts that exceeded the emissions measured at T=0 at both sites. In contrast to ground-based vehicle traffic, test pass intervals often emit less dust than the static benchline control plot (proxy for 0 pass) and emissivity does not appear to increase with an increasing number of passes.

Overall, the rotorcraft impact results are similar to the surface strength trends of the static benchline control plot because there was no direct physical contact with the soil suppressant to cause disturbance during testing. The number of passes by the rotorcraft also did not appear to provide any additional information as to soil suppressant performance or

durability. It should be noted, however, that there are limitations to evaluation of rotorcraft impacts to soil suppressant performance. First there was no direct contact with the ground by rotorcraft that would typically occur during landing and takeoff operations. Such contact would result in physical disruption of a suppressant to cause rotorwash-driven degradation, which would likely compromise performance. Second, aircrew and support personnel, as well as vehicle traffic, would likely occur in areas of rotorcraft operations (e.g. fueling, loading/off loading), which would result in degradation of the soil suppressant in a similar manner to vehicular impacts. One critical question that is not addressed by this test design, but should be considered for future TOPs, is how well a suppressant will hold up to rotorcraft activity if the suppressant was previously degraded or impacted in areas and then subsequently subjected to rotorwash.

3.3 Evaluation of Surface Measurement Methods

Several instruments were used to quantify and record impacts to the soil surface during field testing. Geotechnical properties of penetration resistance and shear strength were conducted using the E-284 dial type pocket penetrometer and E-285 pocket vane shear tester (both manufactured by GeoTest Instrument Corp.), respectively. Dust emission (PM10) was measured using the PI-SWERL. Digital photographs were also taken throughout all test cycles to document the changes in surface appearance. This section examines the overall utility of each of the instruments and methods in the evaluation of soil suppressant performance and durability.

3.3.1 Surface Strength Measurements

The pocket penetrometer and pocket vane shear tester used in this study to measure surface strength properties of the suppressant crust provided useful information about changes in surface strength on the control plots and across all traffic impact types. Surface strength properties measured by both instruments provided easily obtainable data demonstrating the number of passes (vehicle and pedestrian traffic) required to produce a considerable decrease in suppressant performance, as well as an assessment of the durability throughout the entire test cycle. These instruments are inexpensive and can be readily used by technical personnel with minimal training.

Potential problems arose when collecting data from surfaces where the measuring capabilities of one or both instruments were regularly exceeded, typically due to high suppressant crust strength when not enduring testing impacts. In the present study, these

instances commonly occurred when testing static benchline control plots, especially at MMDC, and rotorcraft test plots at SDZ and LPDZ. To obtain accurate measurements of geotechnical properties such as shear strength and penetration resistance, instruments appropriate for the testing of "hard" surfaces with greater measurement ranges should be employed, such as those used during soil laboratory materials testing.

3.3.2 Dust Emissivity Measurements

The PI-SWERL was used in this study to rapidly and cost-effectively measure the relative PM10 dust emissivity of different surfaces and for different traffic impacts. The PI-SWERL directly measured and quantified the dust emission of these surfaces, thereby allowing changes of the control plots and traffic test plots to be detected over the test time intervals. The performance of the PI-SWERL remains unclear for the testing of rotorcraft test plots compared to the control and ground-based traffic impact plots. The negligible changes that occurred over the test time intervals and test pass intervals at the rotorcraft test plots may be beyond the resolution of the PI-SWERL measurement capabilities. Because the surface was not directly impacted and disturbed during the test pass intervals, there was relatively low dust emission measured at these plots. Alternatively, such low dust emissions may also be used to quantify the degree of performance and durability of the suppressant.

3.3.3 Crust Thickness and Visual Assessment

Measured crust thickness was generally lower at MMDC than other study sites, ranging from 0.47 to 0.59 in (12 to 15 mm), with an average of 0.51 in (13 mm). Crust thickness at SDZ and LPDZ ranged from 0.47 to 0.75 in (12 to 19 mm) and 0.47 to 0.79 in (12 to 20 mm) respectively, both with averages of 0.63 in (16 mm). Because the static benchline control plot at MMDC had generally higher shear strength and penetration resistance than the static benchline control plots at other study sites, such results suggest that crust thickness may not be used unconditionally as a proxy for surface strength characteristics. Rather, crust thickness can be used for an assessment of the relative uniformity of the suppressant application on the test plot areas.

Visual assessment of crust integrity after repeated test pass intervals provided a useful tool. This was accomplished by estimating the percent area within impacted tracks that retained coherent portions and aggregates of suppressant crust. In general, as quantitative descriptions of crust integrity percentage decreased over repeated test pass intervals, surface strength decreased and dust emissions increased. Furthermore, visual

observation and quantification of the crust integrity after repeated test pass intervals proved most useful in conjunction with photographic documentation (Appendix E).

Overall, the soil testing instruments used in this study provided sufficient data to quantitatively evaluate the performance and durability of the application. The instruments provided easily obtainable data demonstrating the number of passes (vehicle and foot traffic) required to produce a considerable decrease in suppressant performance, as well as an assessment of the durability throughout the entire test cycle. The PI-SWERL was used in this study to rapidly and cost-effectively measure the relative PM10 dust emission of different surfaces and for different traffic impacts. The PI-SWERL directly measured and quantified the dust emission of these surfaces, thereby allowing changes of the control plots and traffic test plots to be compared over the test time intervals. Crust thickness was also a useful measure to determine if the application of suppressant was uniformly distributed across the test plots to ensure that the comparisons between measurements during the test cycle are of a representative application. Furthermore, the visual assessment and photographic documentation appear to be useful metrics to show changes in suppressant crust that are time and traffic impact-dependent.

4.0 SUMMARY AND RECOMMENDATIONS

The primary objective of this study is to provide recommendations and guidelines to support future development of a Test Operations Procedure (TOP) for testing soil suppressants for military operations. The following recommendations are based on the results from testing one dust suppressant for this study and may not apply to all dust suppressants subjected to future testing. The results here may generally apply only to soils in desert regions, although most of the test methods (instrumentation, plot layouts) may be suitable for testing in other soil-climatic regimes. Based on the results and discussion presented in the previous sections, recommendations are presented as follows:

<u>Development of test parameters for testing soil suppressants for dust abatement</u>:

- Test procedures used in this study were focused only on testing soil suppressant performance on dust abatement. Additional uses of soil suppressants, such as for erosion control, will likely require a different test design and set of procedures.
- Development of TOP criteria to determine specific performance and durability parameters of soil suppressants for dust abatement are required. Criteria to define performance (ability to limit dust emission from dust-rich soils) and durability (time interval over which a pre-determined level of performance is maintained) are required to develop meaningful TOPs. Determination of specific parameters should be based upon established mission requirements for dust abatement.
- Performance in this study was defined as a significant decrease in soil surface strength or a significant increase in dust emission following a specific type of traffic impact. Other approaches that may be more useful for setting performance levels may include setting a minimum level of performance as being surface strength values that are 50% or higher and dust emission values that are 50% or lower than the mean values between the applied soil suppressant (static baseline) and a disturbed soil with no applied suppressant (disturbed baseline).
- Durability in this study was measured as suppressant performance over a 133 day test period (i.e., applied suppressant was exposed to unmodified environmental conditions over 133 days). Testing for suppressant durability could be based on predetermined performance requirements for a suppressant. For example, military operations may require that the suppressant provide adequate dust abatement for 180 days, requiring that the TOP evaluates durability for at least 180 days of exposure.

- Three soil types used in this study provide reasonable analogs for soils in regions commonly engaged by current military activities in deserts in southwest Asia and the southwest U.S. that have a high potential for dust emission. Consideration of different study sites, representing different soil types, may provide additional information on the impacts of ground-based traffic. The soils used in this study were selected based on relatively high fractions of fine sand, silt, and clay that are typical of relatively flat desert terrain occupied on a large-scale by U.S. military forces. Soils with lower silt and higher sand or gravel contents, typical of many unimproved roads in desert regions, might be more appropriate for the testing of some types of suppressants for reducing dust emission related to traffic on dirt and gravel roads.

<u>Use of control plots to evaluate suppressant performance and durability</u>

- Control plots provide different types of data that may be necessary for monitoring and evaluating suppressant performance and durability criteria.
- A disturbed baseline plot provides a measure of maximum potential for dust emission and provides the best data to directly evaluate soil suppressant performance. Measurement of the disturbed baseline at each time interval provides a measure of any changes in dust emissivity and surface strength that might have occurred over the time period of testing. This parameter will vary over the test interval if environmental conditions change considerably (especially when soil moisture and relative humidity are variable).
- A static baseline control plot provides a metric for natural recovery of the surface over the test interval (capability for a decrease in dust emission over time due to formation of a natural soil crust). Natural recovery may result in a systematic decrease in dust emission over time, resulting in a decrease in dust emission levels that is nearly equal to that of the applied soil suppressant. This natural recovery may mask or overshadow concomitant changes in soil suppressant dust abatement. Use of static baseline plots may be critical in the evaluation of durability over time intervals >100 days.
- A static benchline control plot provides a direct measure of soil suppressant durability by providing a direct measure of surface strength and dust emission at different time intervals over the test period.
- Of note, the disturbed baseline plot data could be partially replaced with data from measurements made at T=0 on the static baseline plots to reduce time and resources

for data collection, or if significant changes in environmental conditions are experienced.

- The design of the three control plots can be used alone to test the durability performance of soil suppressants for TOPs where no physical impact to the suppressant from military equipment or personnel is expected.

Types of traffic impacts used in evaluating suppressant performance

- The combination of traffic impact plots and the instrumentation used in this study demonstrates that determining suppressant performance and durability can be readily established.
- Testing of ground-based traffic impacts may not require multiple vehicle types. The use of only a single wheeled vehicle, perhaps supplemented with a heavy-tracked vehicle, will provide adequate data for evaluating performance and durability requirements.
- The number of passes (vehicular, foot) for testing ground-based traffic impacts requires consideration of desired performance and durability standards.
- The methods used in this study may not adequately test the actual impact of rotorcraft on soil suppressant that will occur during landing and takeoff or that is associated with ground-based support. Any physical disruption to the suppressant from vehicle, foot, or aircraft contact with the soil suppressant will likely result in degradation or damage by the rotorwash that may compromise the integrity of the suppressant. Development of TOPs for evaluation of soil suppressants in areas of aircraft operation may require additional testing to determine performance and durability in areas where where physical disruption of the suppressant is likely to occur in addition to rotorwash.

Instrumentation and methods used in testing performance and durability

- The soil testing instruments used in this study, including the pocket penetrometer, pocket vane shear tester, and the PI-SWERL (Portable *In Situ* Wind ERosion Laboratory), provided excellent data to quantitatively evaluate the performance and durability of the suppressant.
- Other instrumentation, such as a cone penetrometer and nuclear density gauge, would be useful for characterizing the soil prior to testing, to better assess

differences in potential bearing capacity and subsurface soil strength. This would provide useful information to evaluate the overall trafficability of the soil surface, which in turn could be used to assess the performance of the strength of the suppressant during traffic impact testing.

- PI-SWERL provided an efficient and portable method to quantify dust emission on different surfaces as a function of traffic type, disturbance, and suppressant. Previous studies of soil suppressant performance have largely relied upon subjective observational data or have used passive measures such as dust traps to measure emitted dust. Although PI-SWERL is cost-effective relative to a wind tunnel, limitations for the use of PI-SWERL include the high cost of the instrumentation and an understanding that operation of the instrumentation requires specialized knowledge of soils and substantial instrument training.
- Crust thickness should not be used as a proxy for surface strength properties, but can be used to determine if the application of suppressant was conducted evenly across the test plots.
- Visual assessment and photographic documentation appear to be useful metrics for time-dependent changes of the suppressant crust after impact, as well as to relay information by a more qualitative, observational method.

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6.0 TABLES

Table 1. Methods Employed in Previous Military-Relevant Dust Suppression Studies

Study/Traffic Type	*Qualitative Methods*	*Quantitative Methods*
Roa-Espinosa and Mikel 2004/Rotorcraft	Visual estimation of dust Operator commentary	Passive dust collection
Rushing et al. 2005/ Wheeled Vehicles	Visual estimation of dust Road condition index	Troxler density and moisture Active dust collection USCS classification Dynamic cone penetrometer
Rushing et al. 2006/ Wheeled Vehicles	Visual estimation of dust Road surface quality	Troxler density and moisture Active dust collection USCS classification
Tingle et al. 2004/ Rotorcraft	Visual estimation of dust Road surface quality	Troxler density and moisture Active and passive dust collection Torvane shear device Geonor vane shear device Dynamic cone penetrometer

Table 2. Test Layout Size and Suppressant Application Characteristics

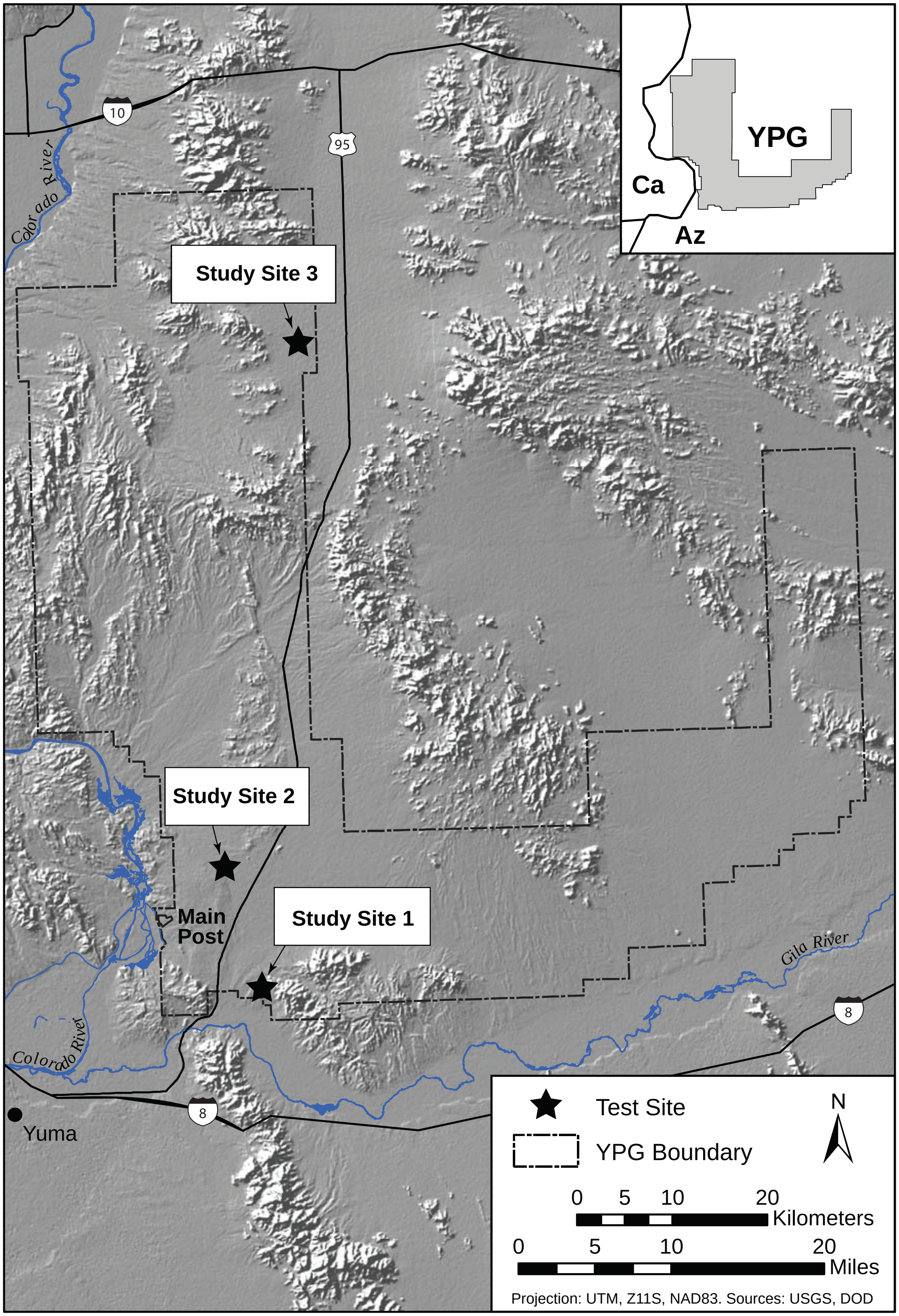
Site (Layout Type)	*Size (Acres)*	*Dilution Ratio (H_2O:suppressant)*	*Application Rate (Gallons/Acre)*
MMDC (Ground)	1.079	4.6:1	908
SDZ (Ground)	1.308	4.9:1	929
SDZ (Rotorcraft)	2.066	6.3:1	915
LPDZ (Rotorcraft) SF	2.066	6.3:1	915
LPDZ (Rotorcraft) DF*	2.066	6.3:1	915

*The formulation applied at LPDZ DF was TerraLOC® Standard; at all other sites the formulation was TerraLOC® Xtra.

Table 3. Traffic Type Characteristics, Testing Locations, and Passes per Test

Traffic Type	*Weight*	*Site Locations*	*Test Pass Intervals*
APC M113	19,960 pounds (lbs) 9054 kilograms (kg)	Muggins Mesa Dust Course Sidewinder Drop Zone	5, 10
STRYKER ESV	44,000 lbs 19,958 kg	Muggins Mesa Dust Course Sidewinder Drop Zone	5, 10, 15
LMTV M1078	17,770 lbs 8060 kg	Muggins Mesa Dust Course Sidewinder Drop Zone	5, 10, 15
HMMWV	5,442 lbs 2,468 kg	Muggins Mesa Dust Course Sidewinder Drop Zone	5, 10, 15
FOOT	145-260 lbs 66-118 kg	Sidewinder Drop Zone La Posa Drop Zone	40, 80, 160
UH-1 Rotorcraft	5,215 lbs 2,365 kg	Sidewinder Drop Zone La Posa Drop Zone	10, 20, 30

7.0 FIGURES

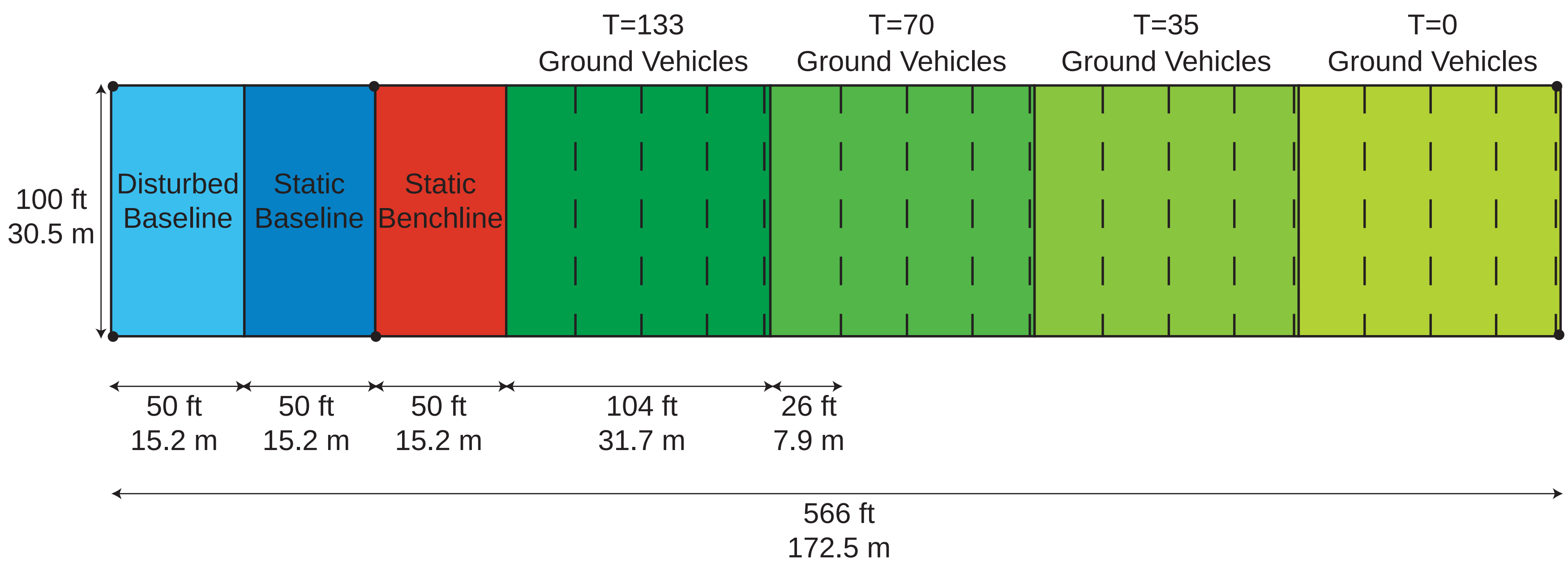


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Test Site Locations

DATE: 01-22-09

FIGURE 1



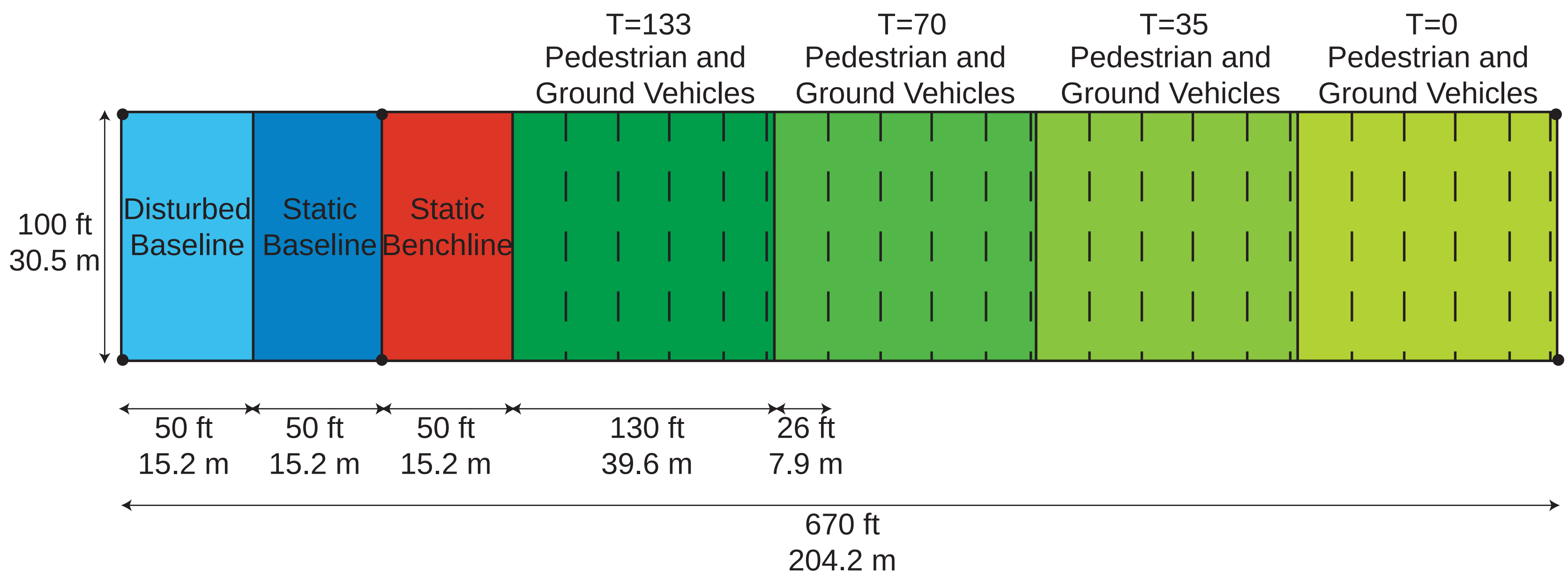
Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING

Muggins Mesa Dust Course Test Layout

DATE: 01-27-09

FIGURE 2



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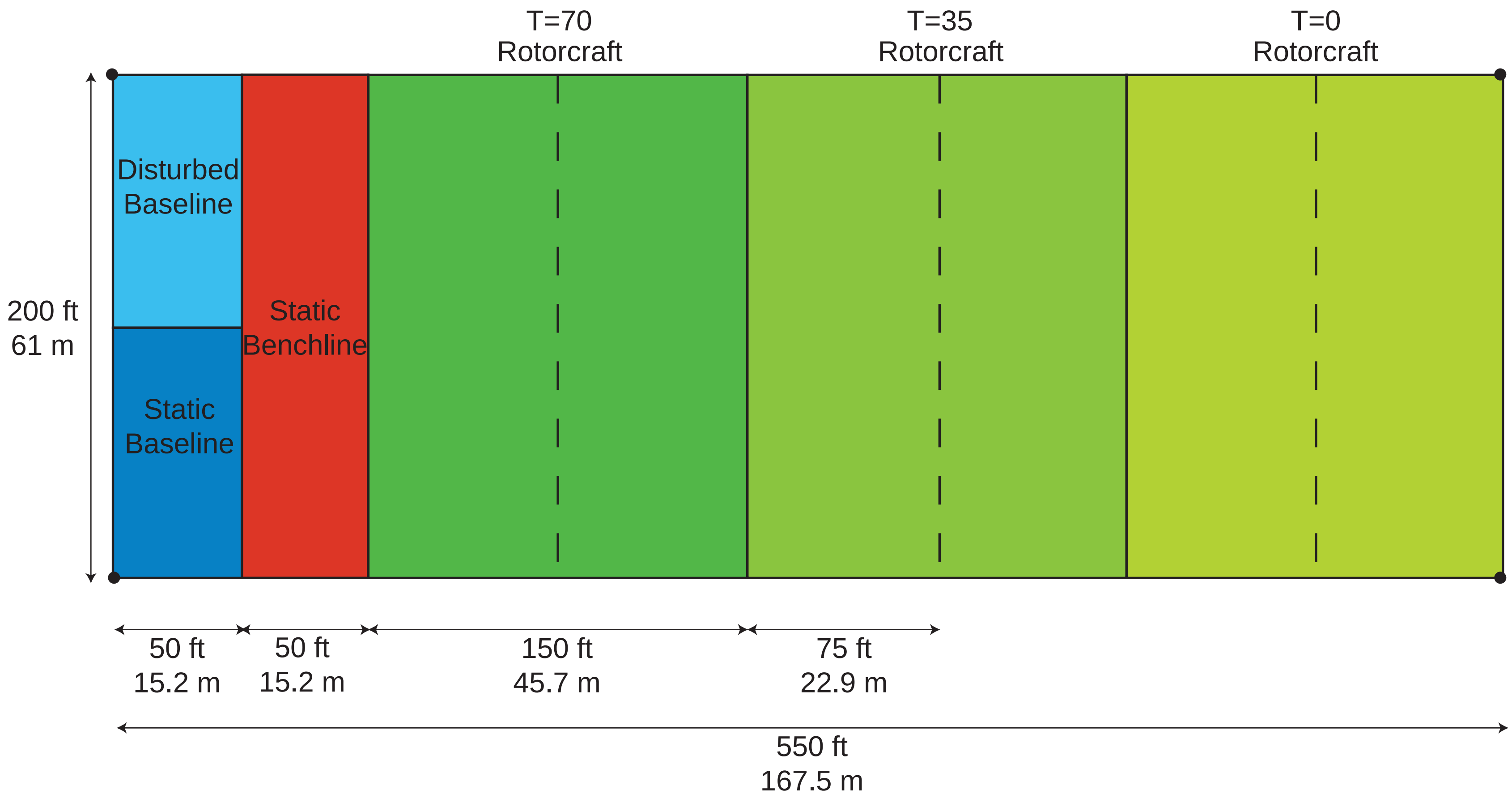
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Ground-Based Traffic Test Layout

DATE: 01-27-09

FIGURE 3

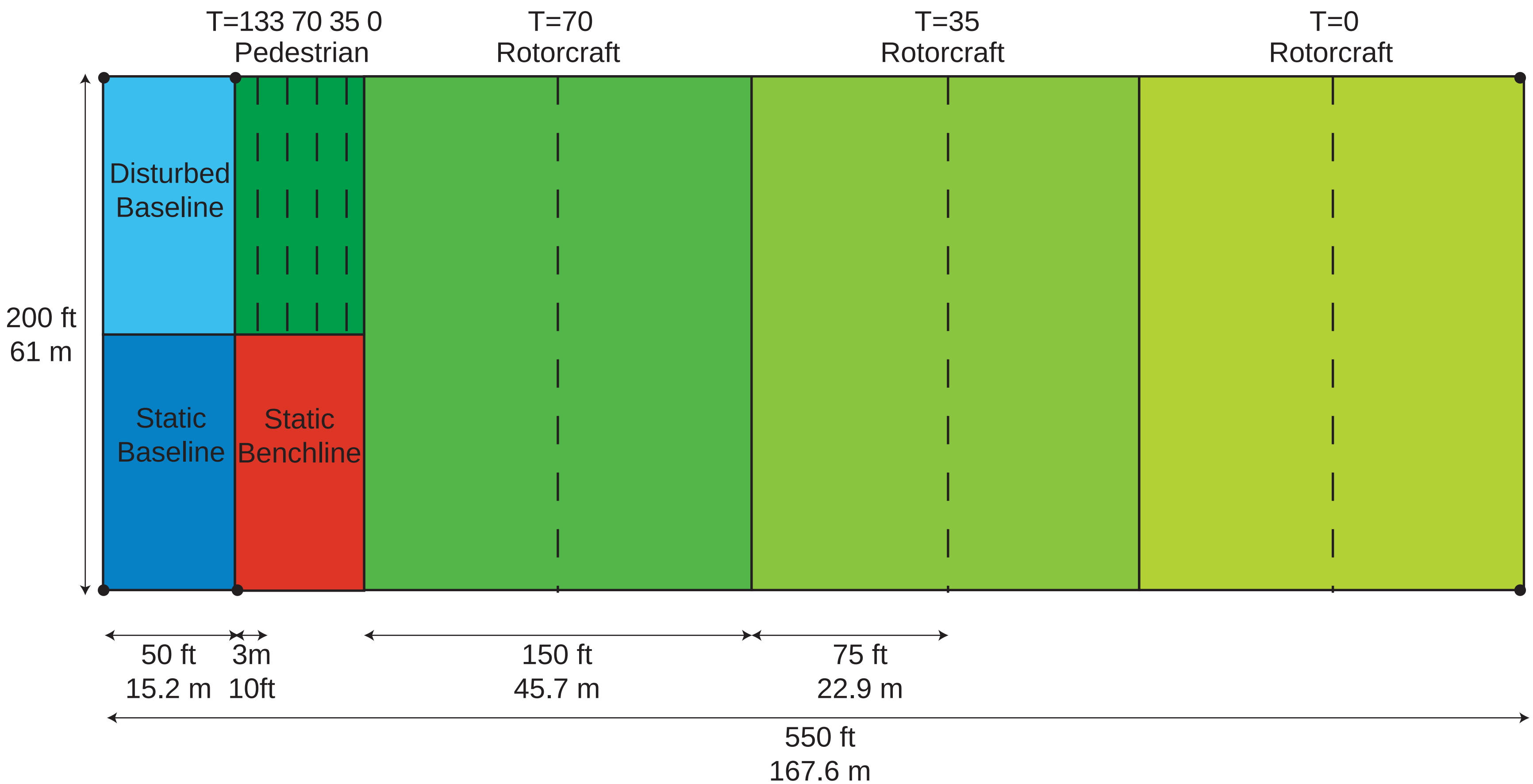


DRI Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Rotorcraft and La Posa Drop Zone DF Test Layout

DATE: 01-27-09

FIGURE 4

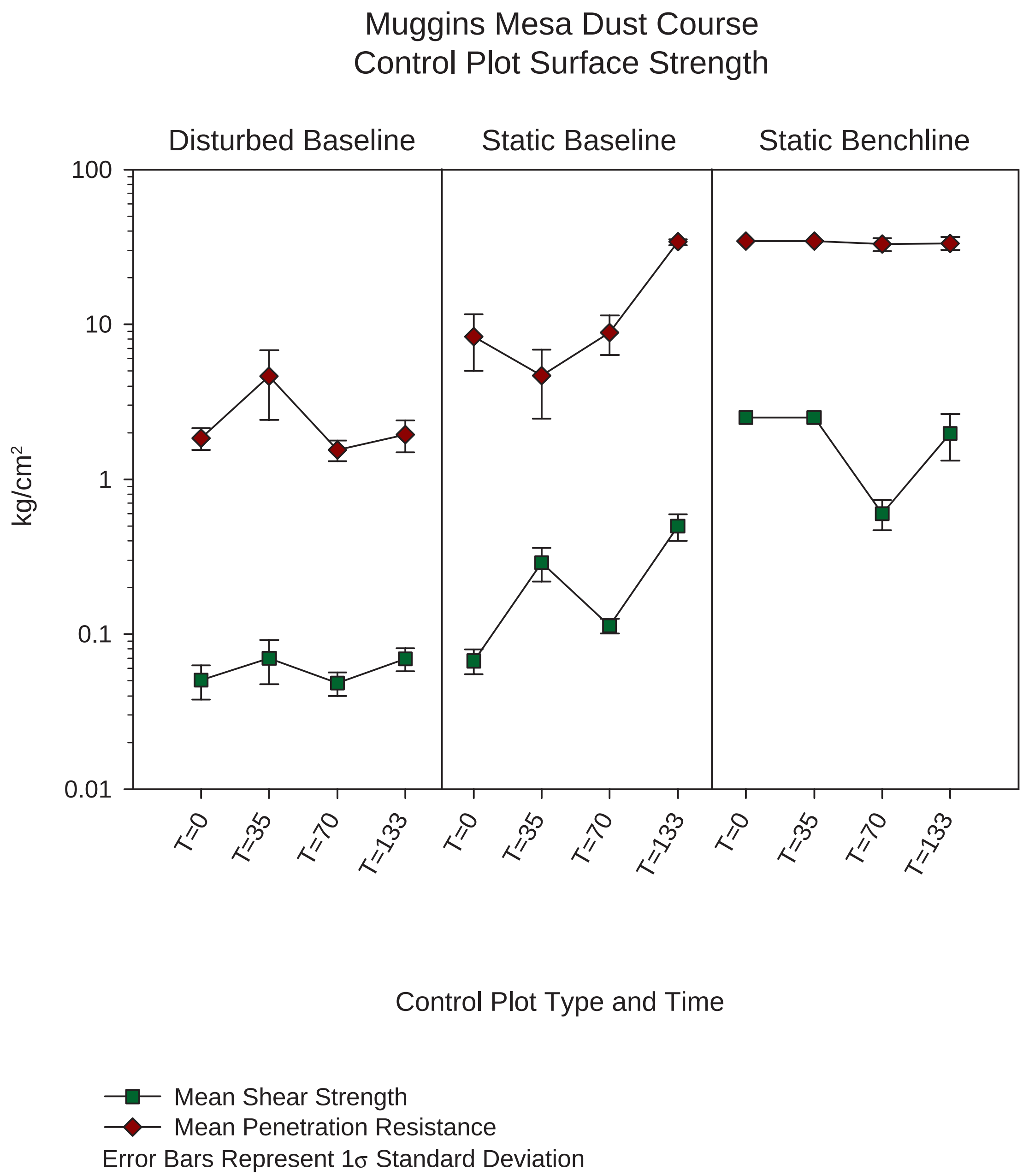


Desert Research Institute

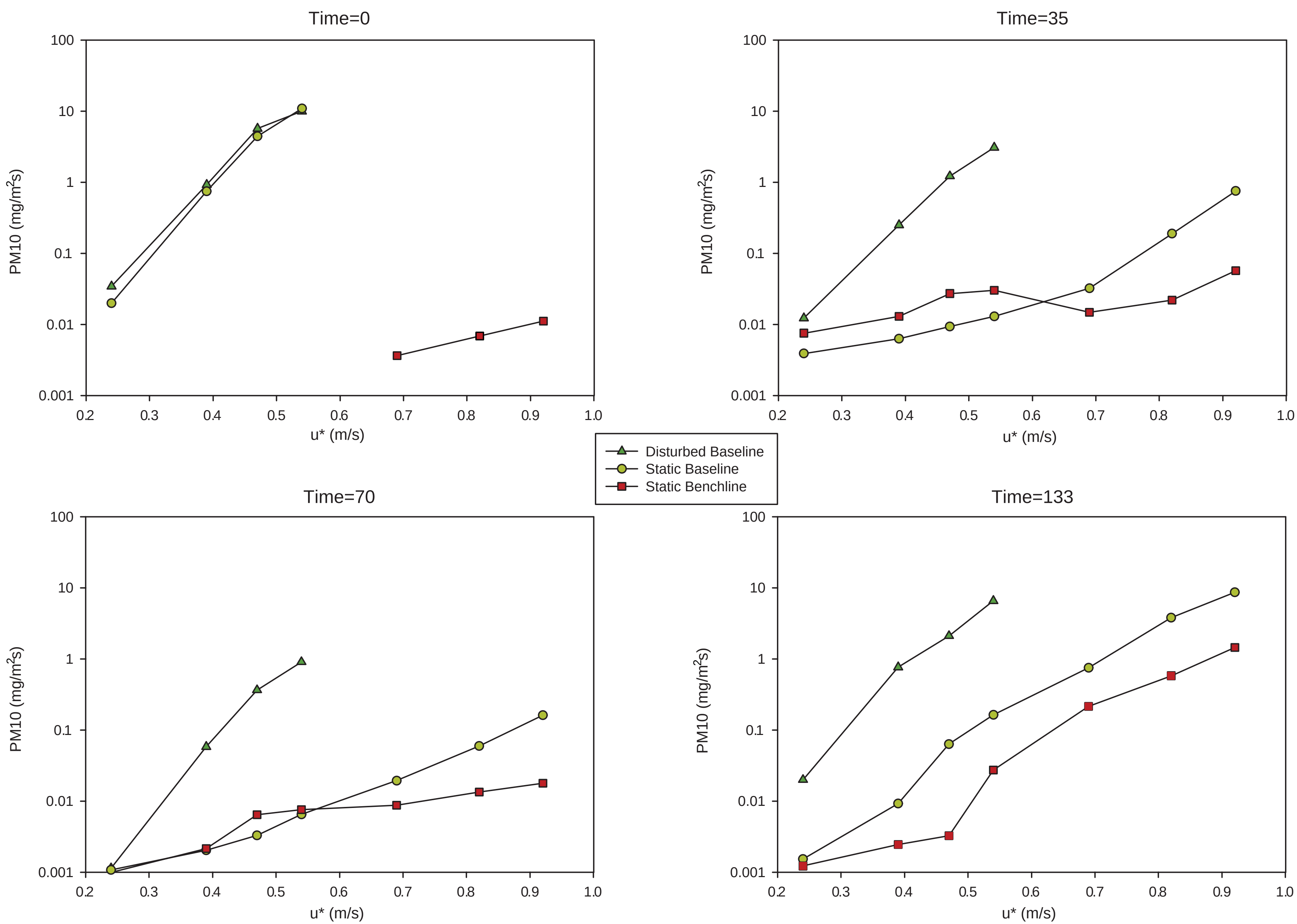
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone SF Test Layout

DATE: 01-27-09

FIGURE 5



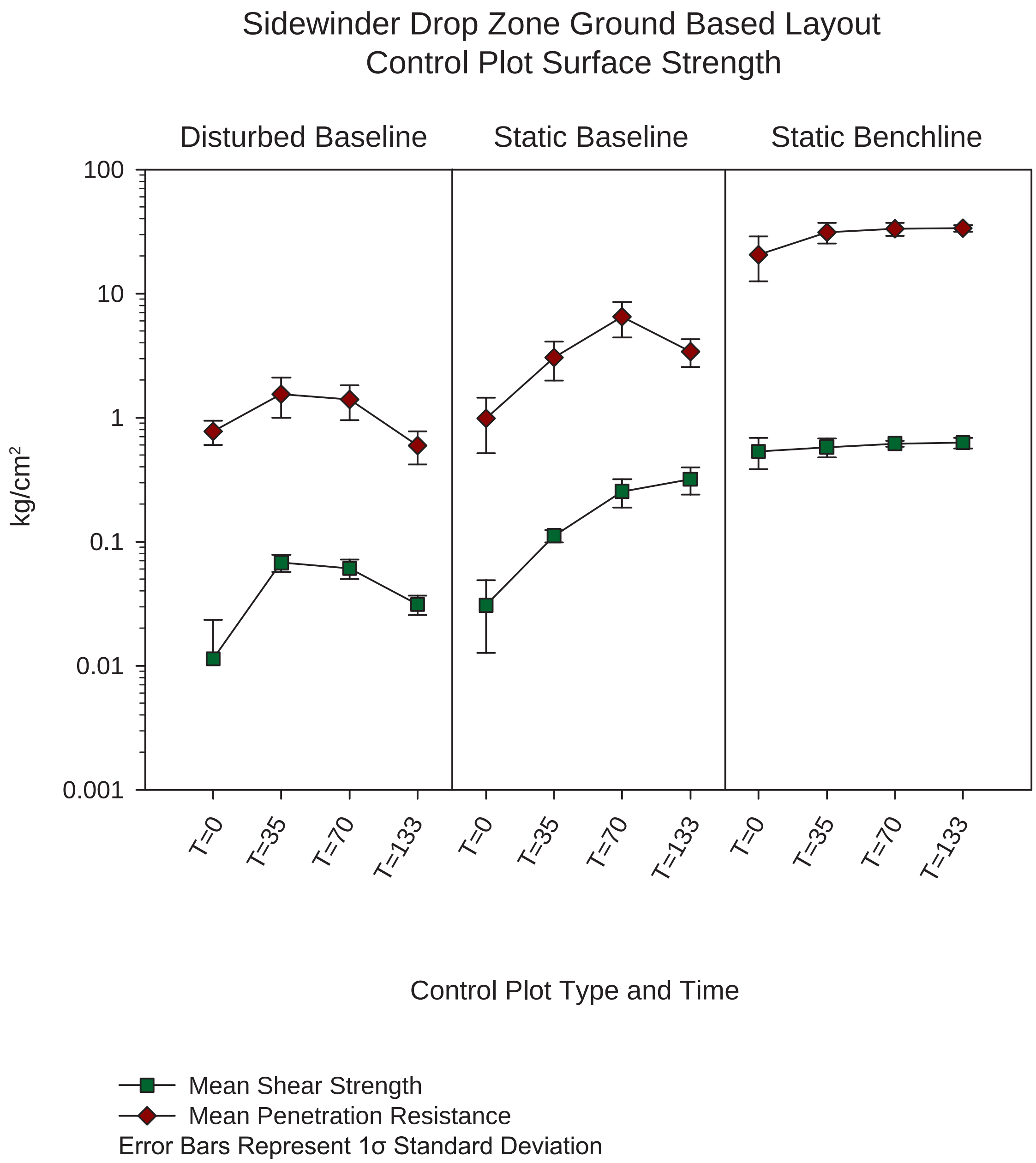
Desert Research Institute	**U.S. ARMY YUMA PROVING GROUND** **DUST SUPPRESSANT TESTING** **Muggins Mesa Dust Course**	DATE: 04-01-09
		FIGURE 6



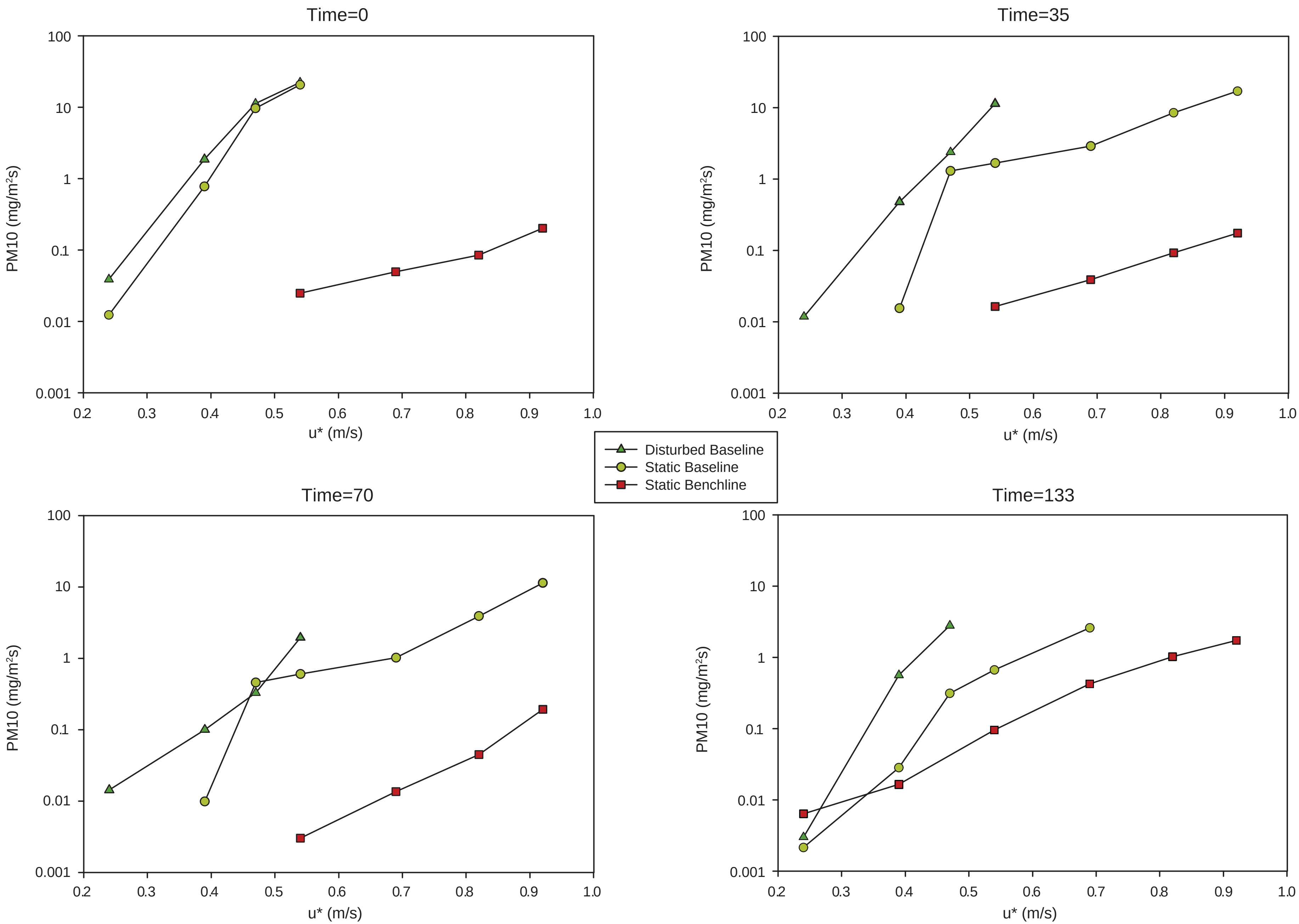
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course Control Plot PM10 Emissions

DATE: 03-11-09

FIGURE 7



Desert Research Institute	**U.S. ARMY YUMA PROVING GROUND** **DUST SUPPRESSANT TESTING** **Sidewinder Drop Zone Ground Based Layout**	DATE: 04-01-09 FIGURE 8

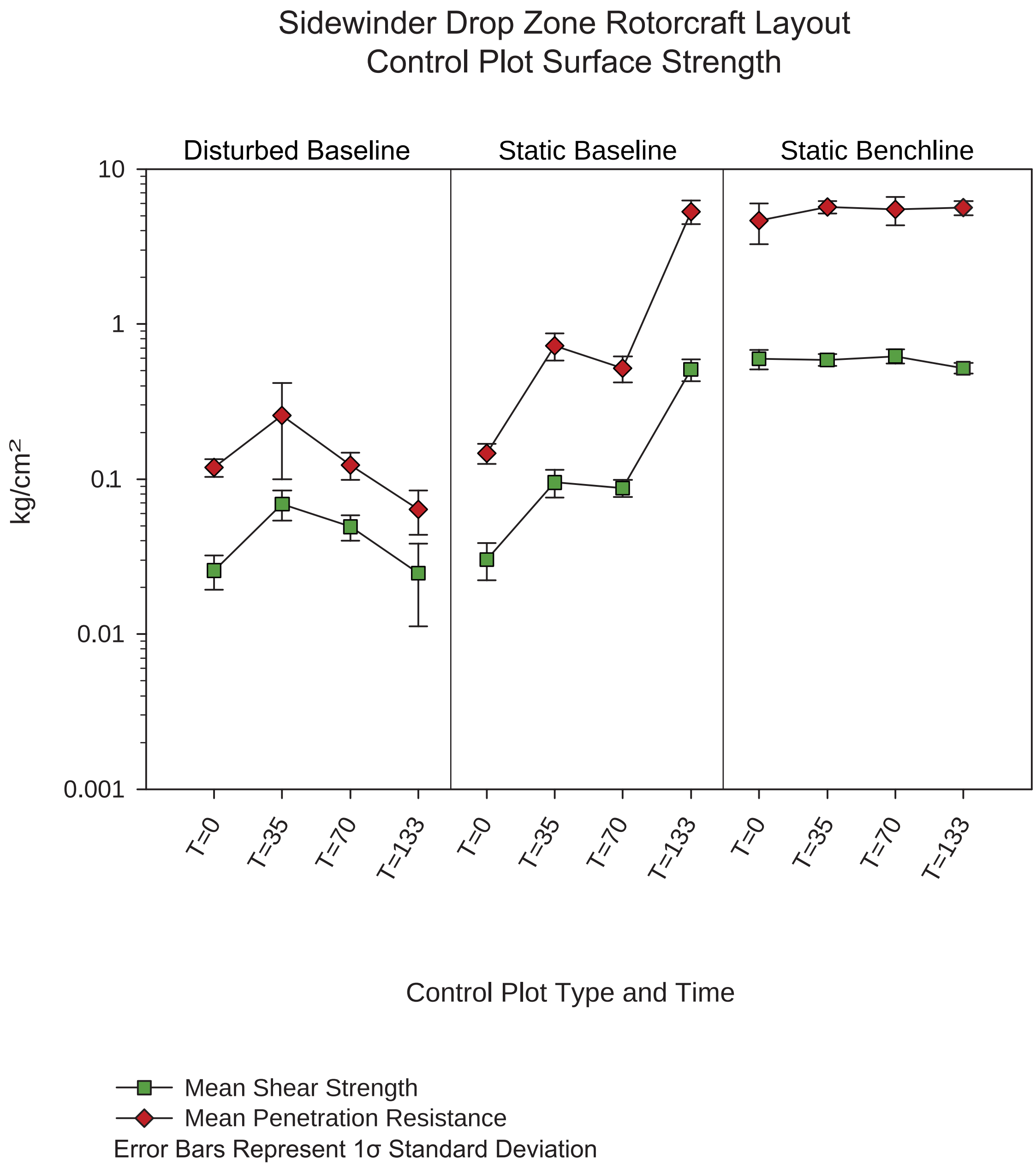


Desert Research Institute

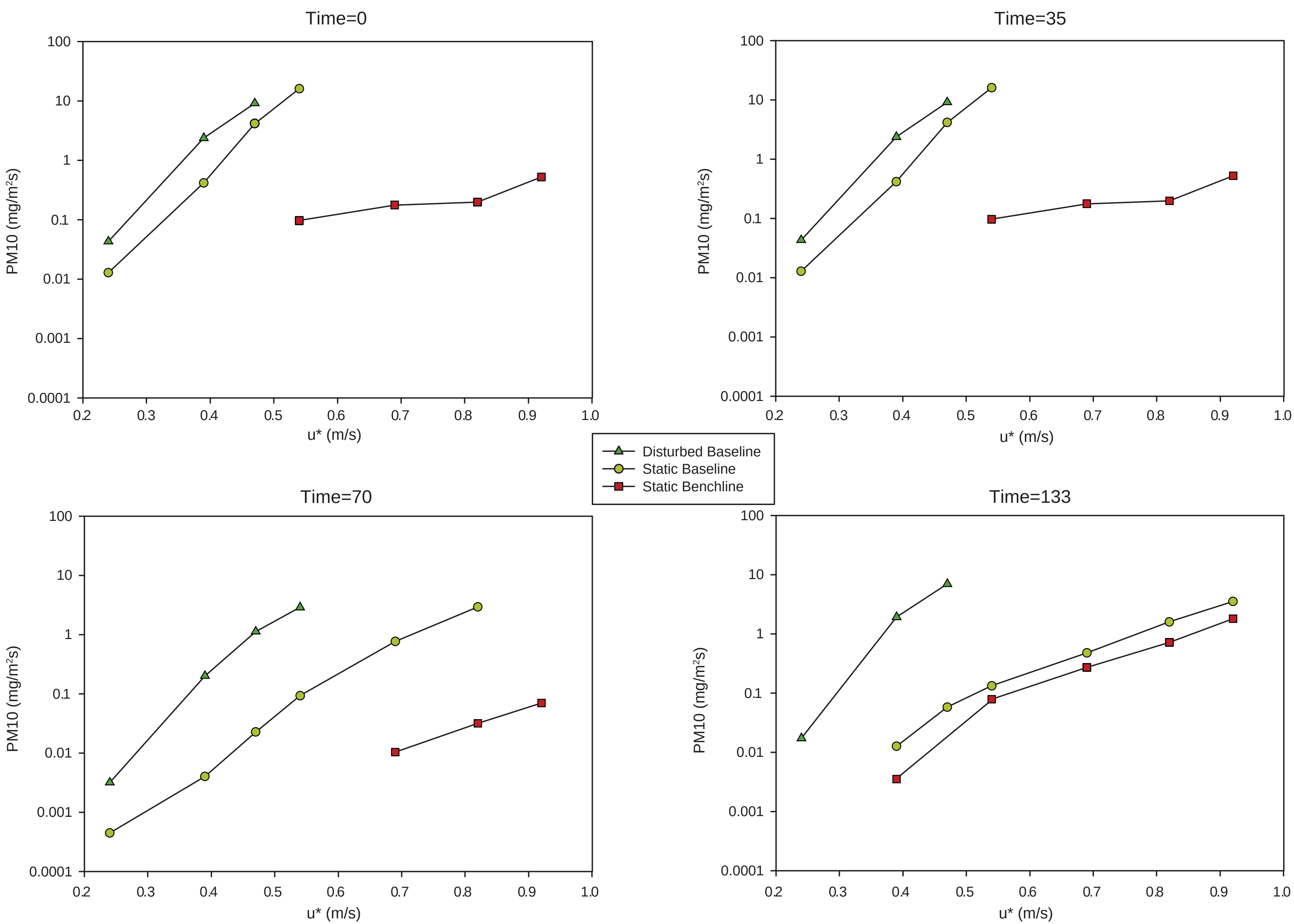
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Ground Based Layout Control Plot PM10 Emissions

DATE: 04-01-09

FIGURE 9



Desert Research Institute	**U.S. ARMY YUMA PROVING GROUND** **DUST SUPPRESSANT TESTING** **Sidewinder Drop Zone Rotorcraft Layout**	DATE: 01-27-09 FIGURE 10

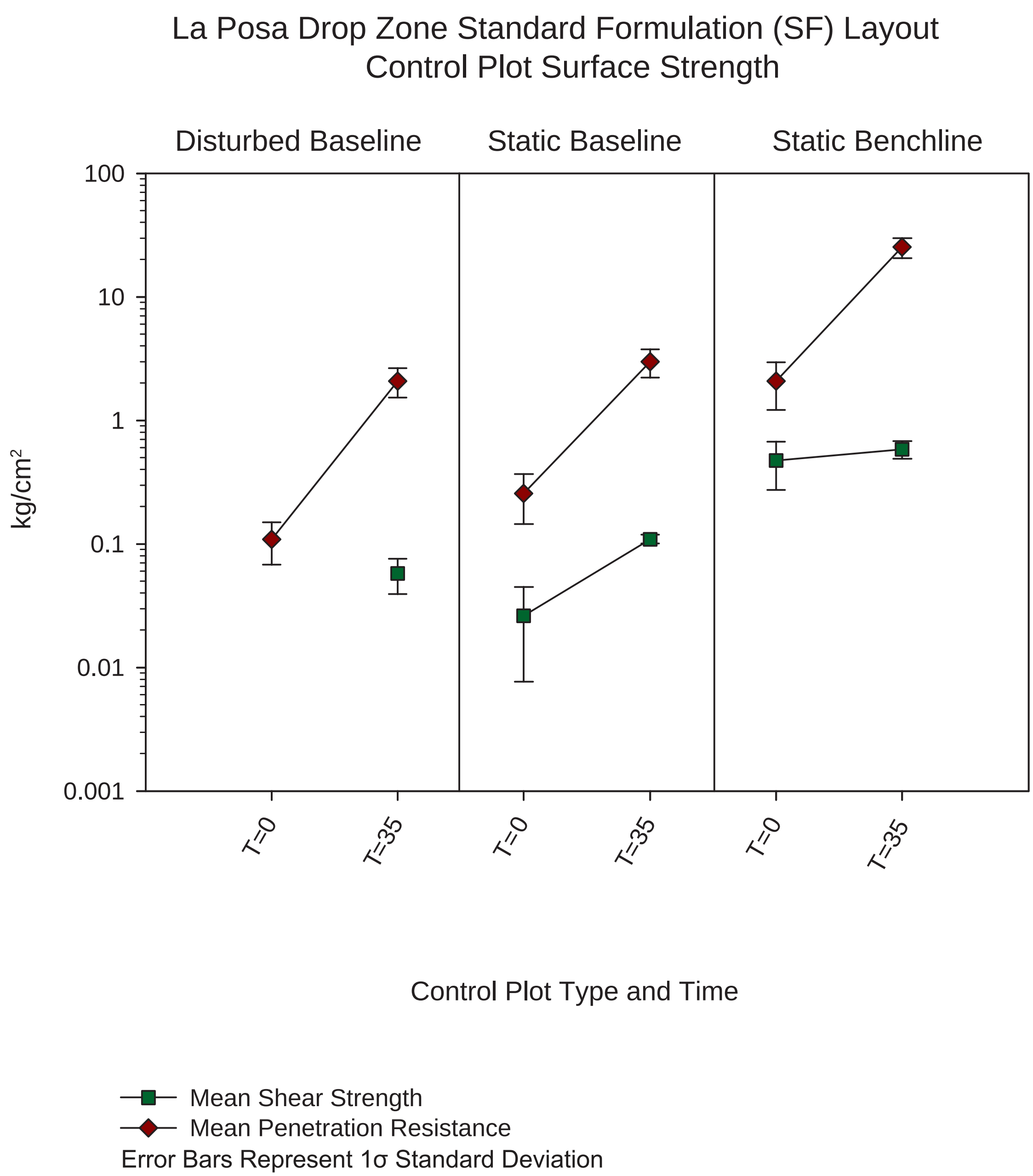


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Rotorcraft Layout Control Plot PM10 Emissions

DATE: 04-01-09

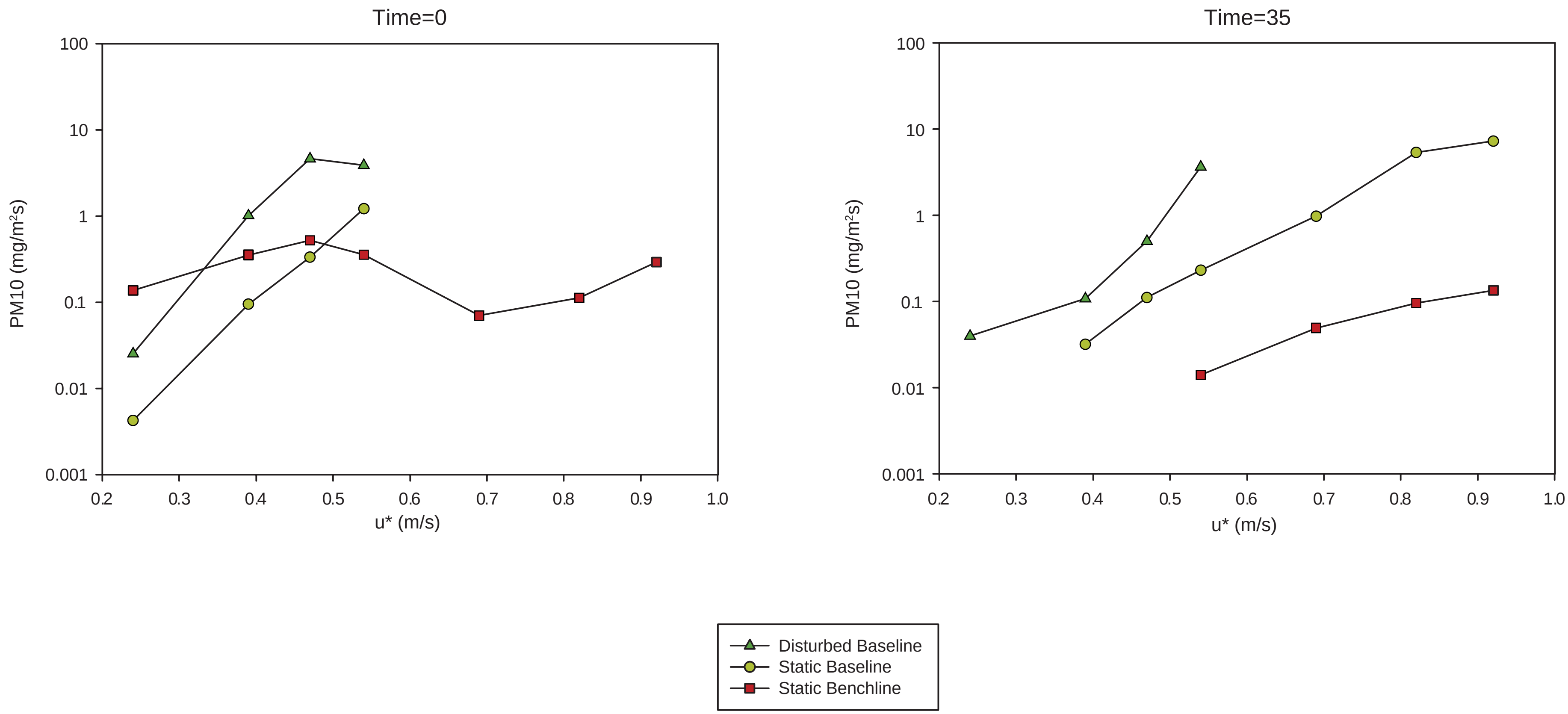
FIGURE 11



U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
La Posa Drop Zone Standard Formulation (SF) Layout

DATE: 04-01-09

FIGURE 12

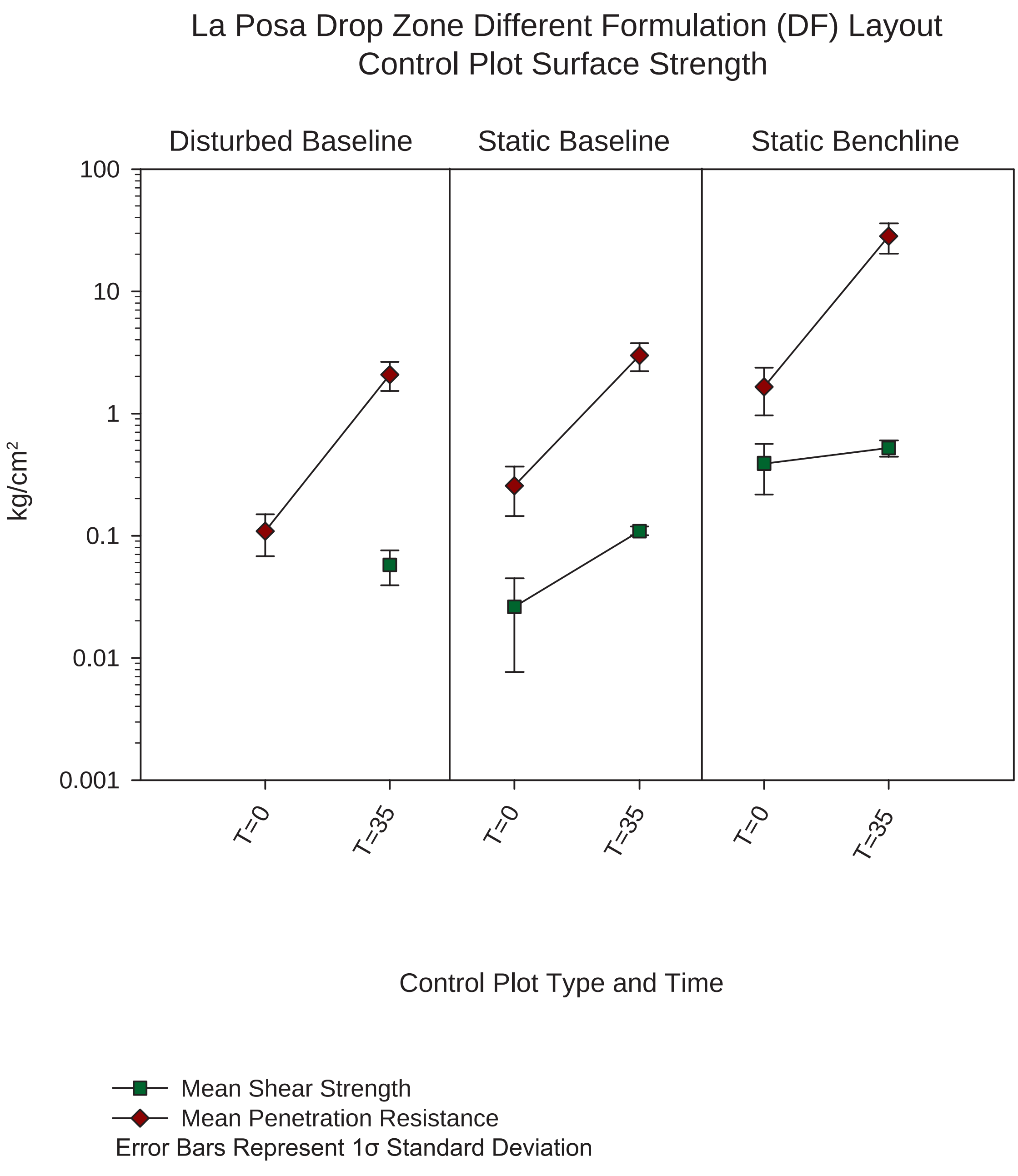


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone SF Layout Control Plot PM10 Emissions

DATE: 04-02-09

FIGURE 13

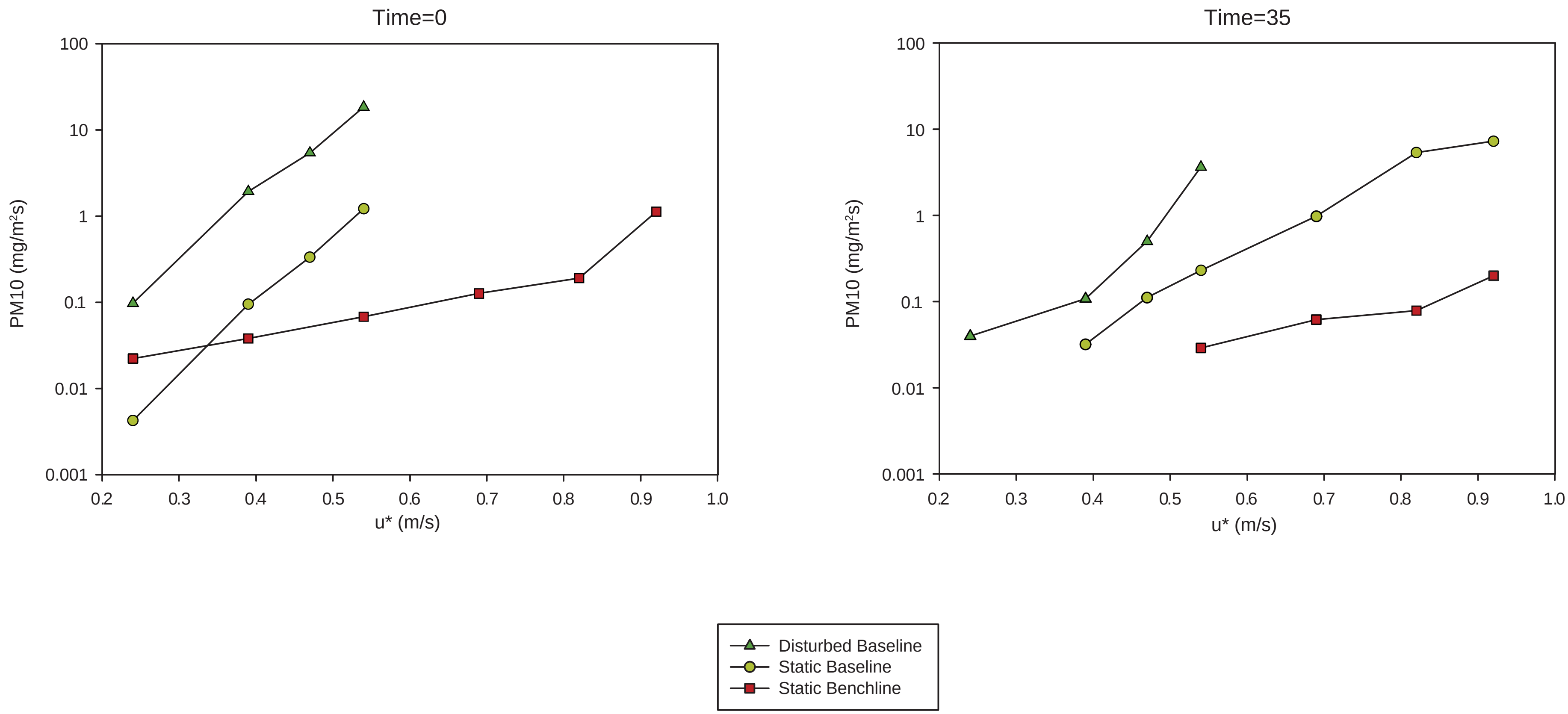


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
La Posa Drop Zone Dilute Formulation (DF) Layout

DATE: 04-01-09

FIGURE 14

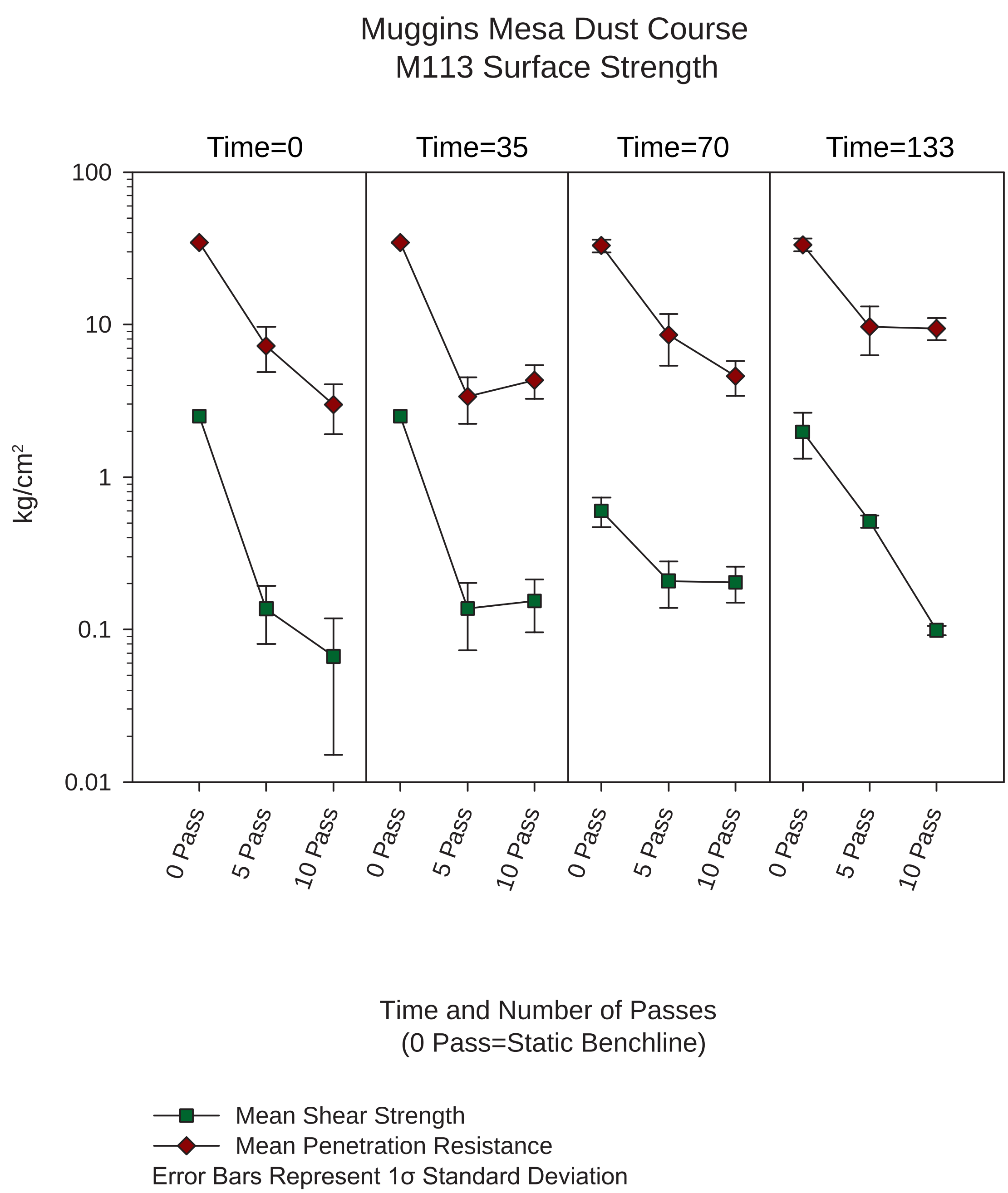


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone DF Layout Control Plot PM10 Emissions

DATE: 04-02-09

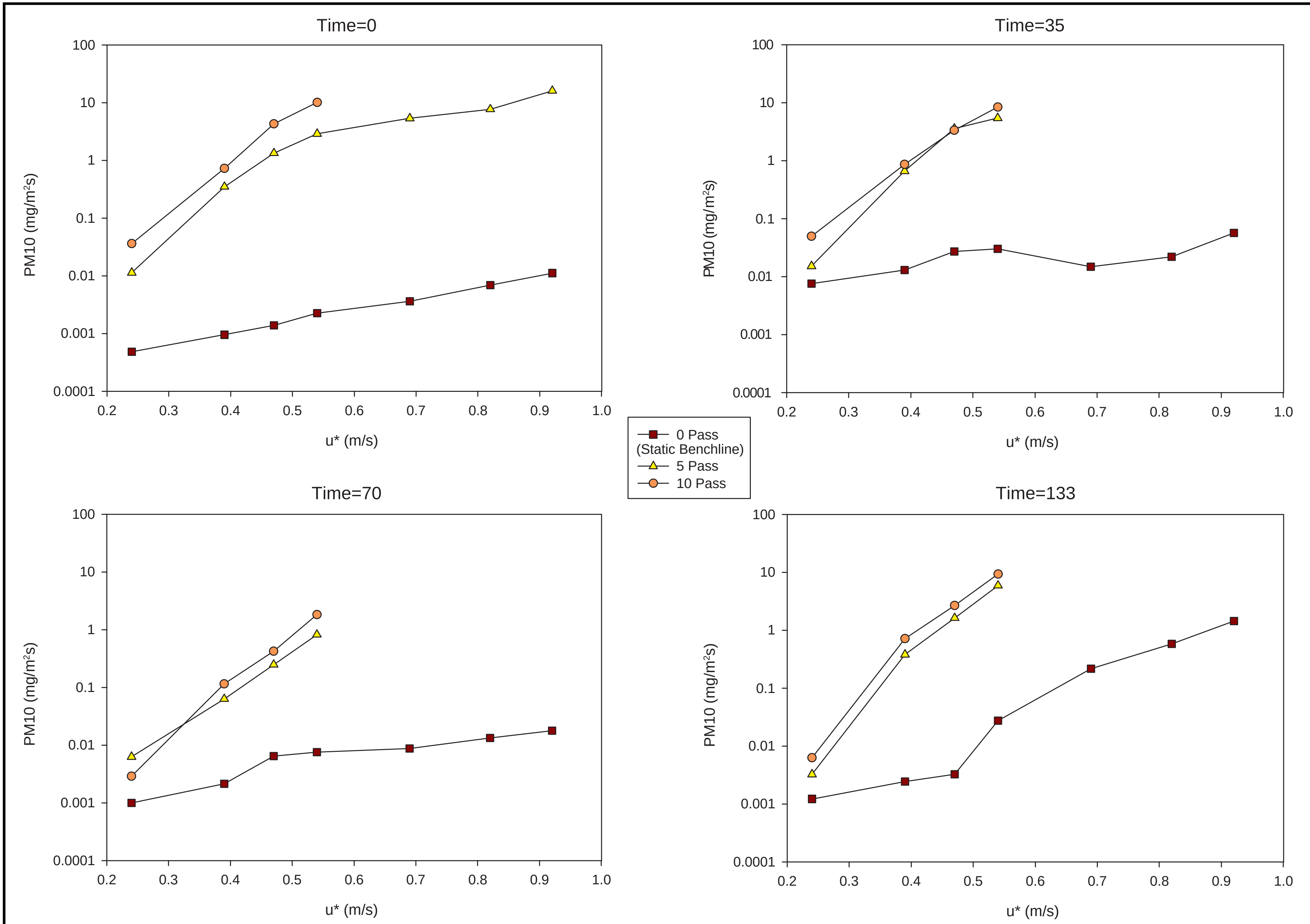
FIGURE 15



U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course M113 Surface Strength

DATE: 06-09-09

FIGURE 16

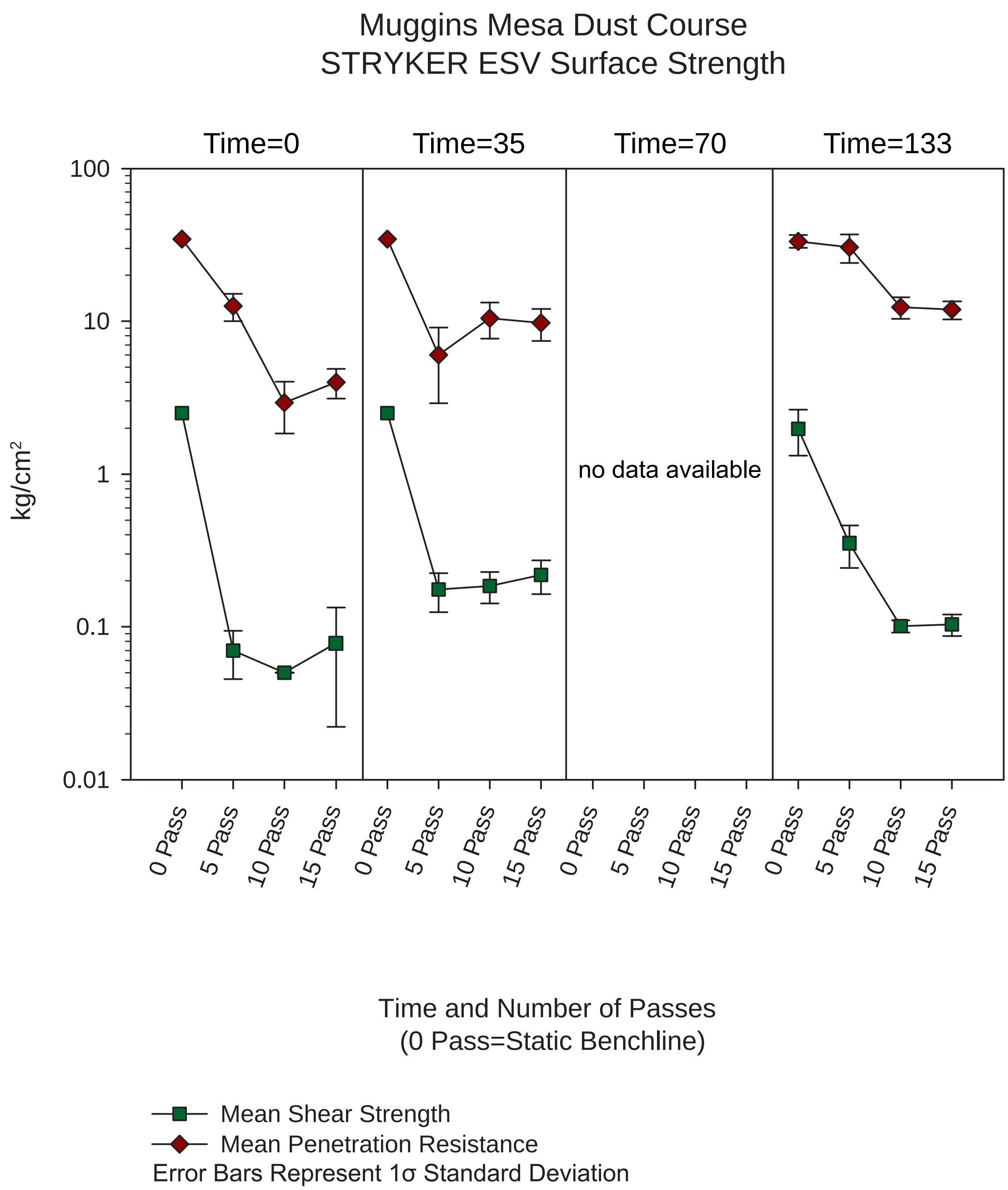


U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING

Muggins Mesa Dust Course M113 PM10 Emissions

DATE: 04-01-09

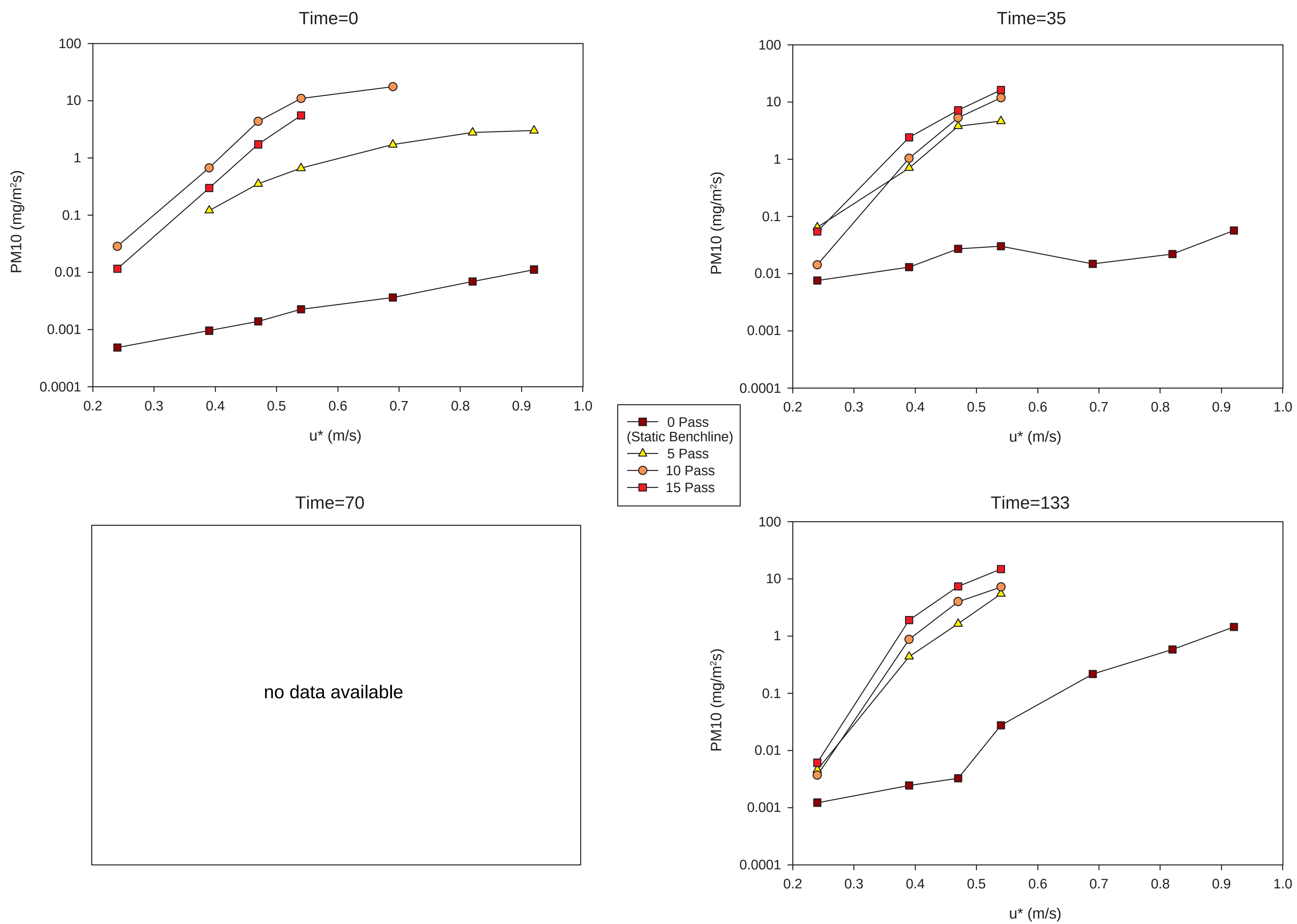
FIGURE 17



U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course STRYKER ESV Surface Strength

DATE: 06-09-09

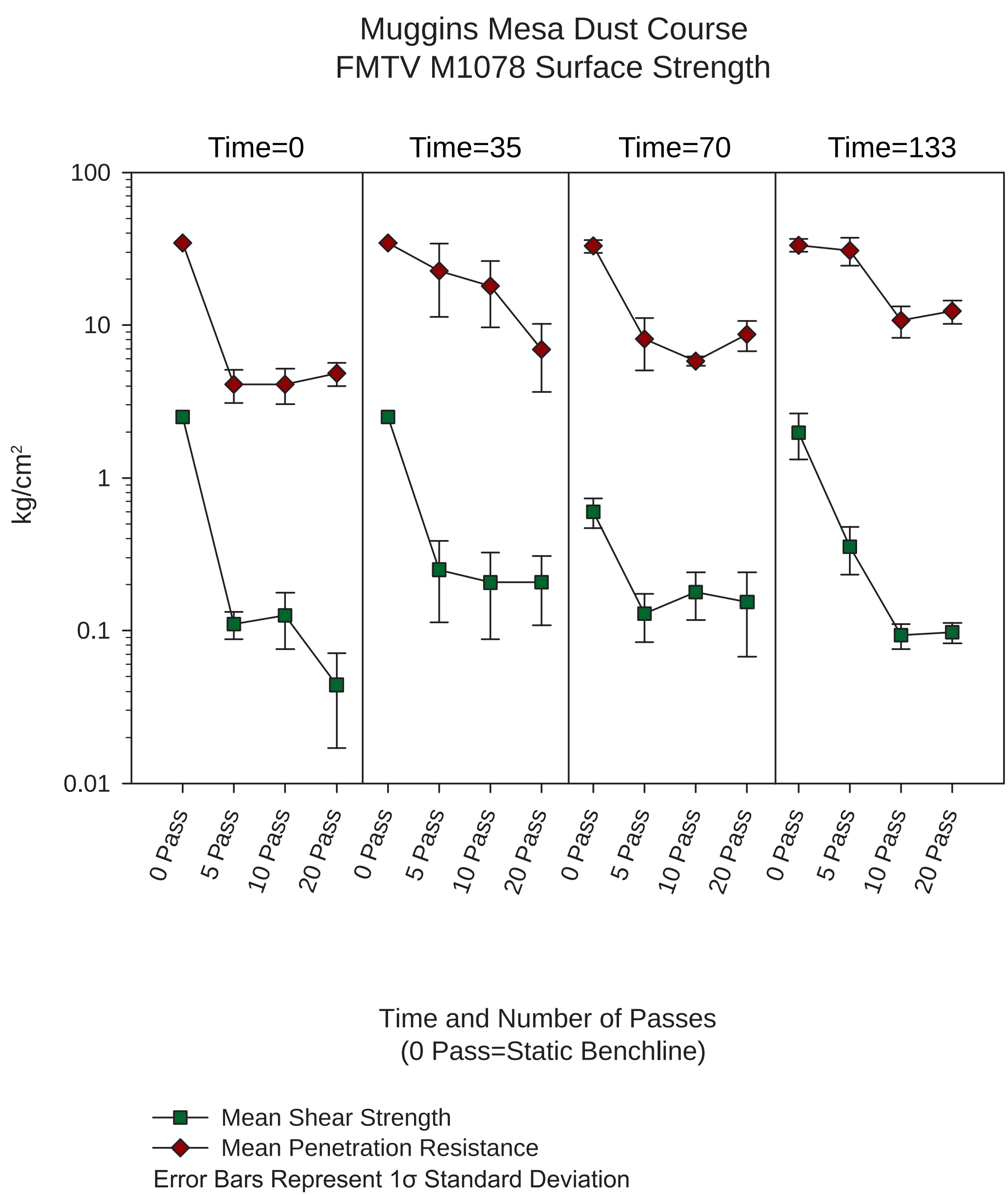
FIGURE 18



U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course STRYKER ESV PM10 Emissions

DATE: 04-01-09

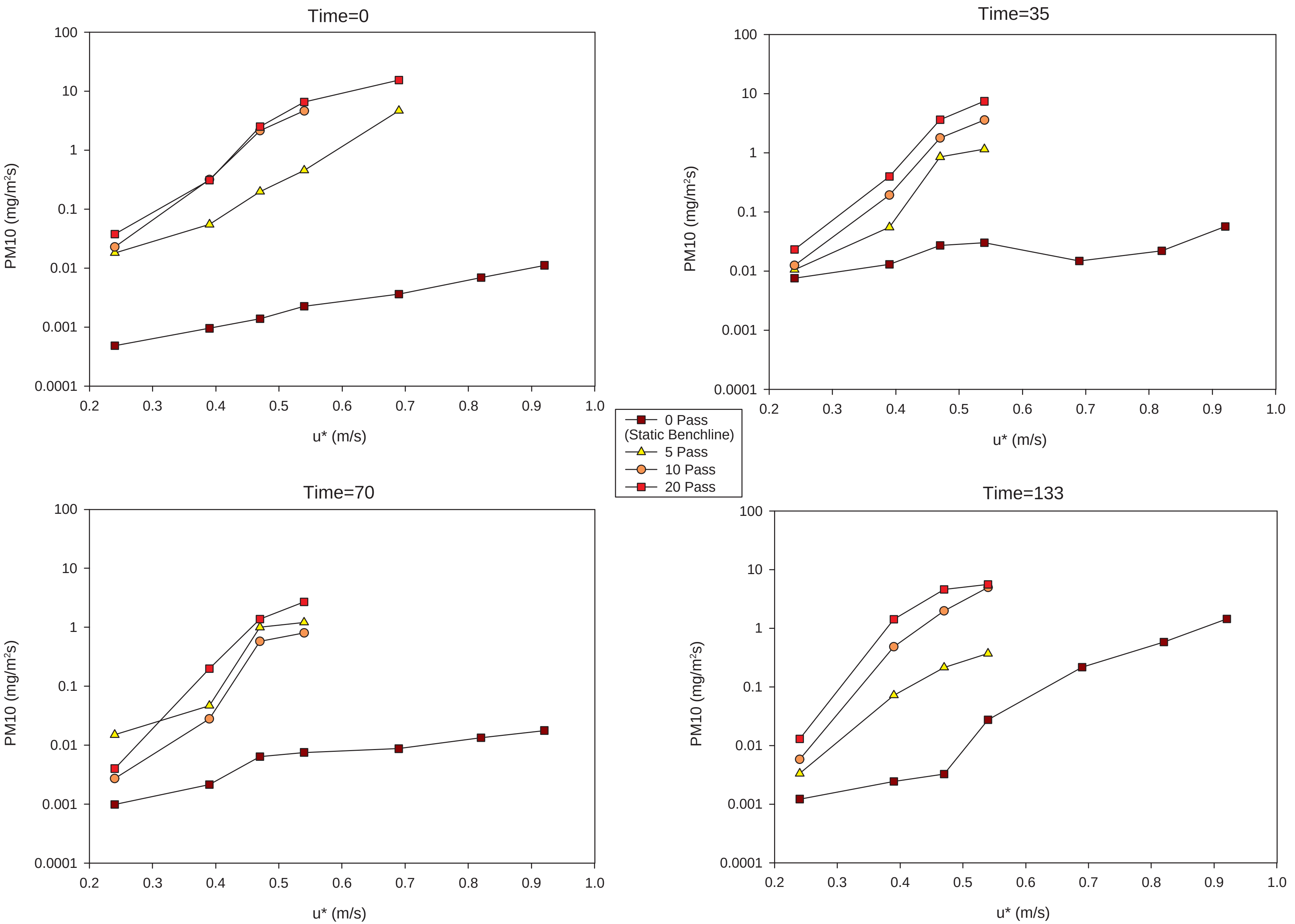
FIGURE 19



U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course FMTV M1078 Surface Strength

DATE: 06-09-09

FIGURE 20

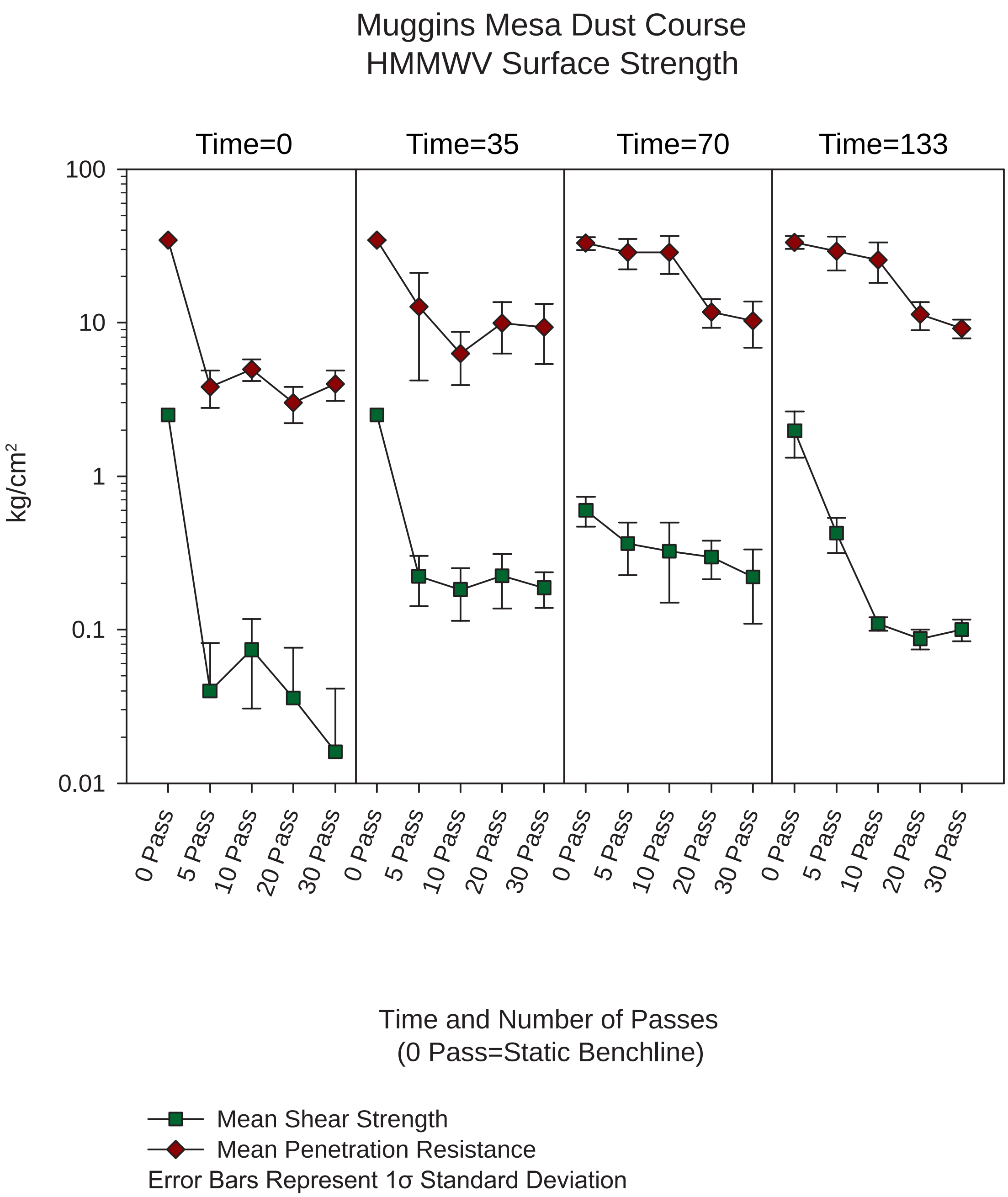


DRI Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course FMTV M1078 PM10 Emissions

DATE: 04-01-09

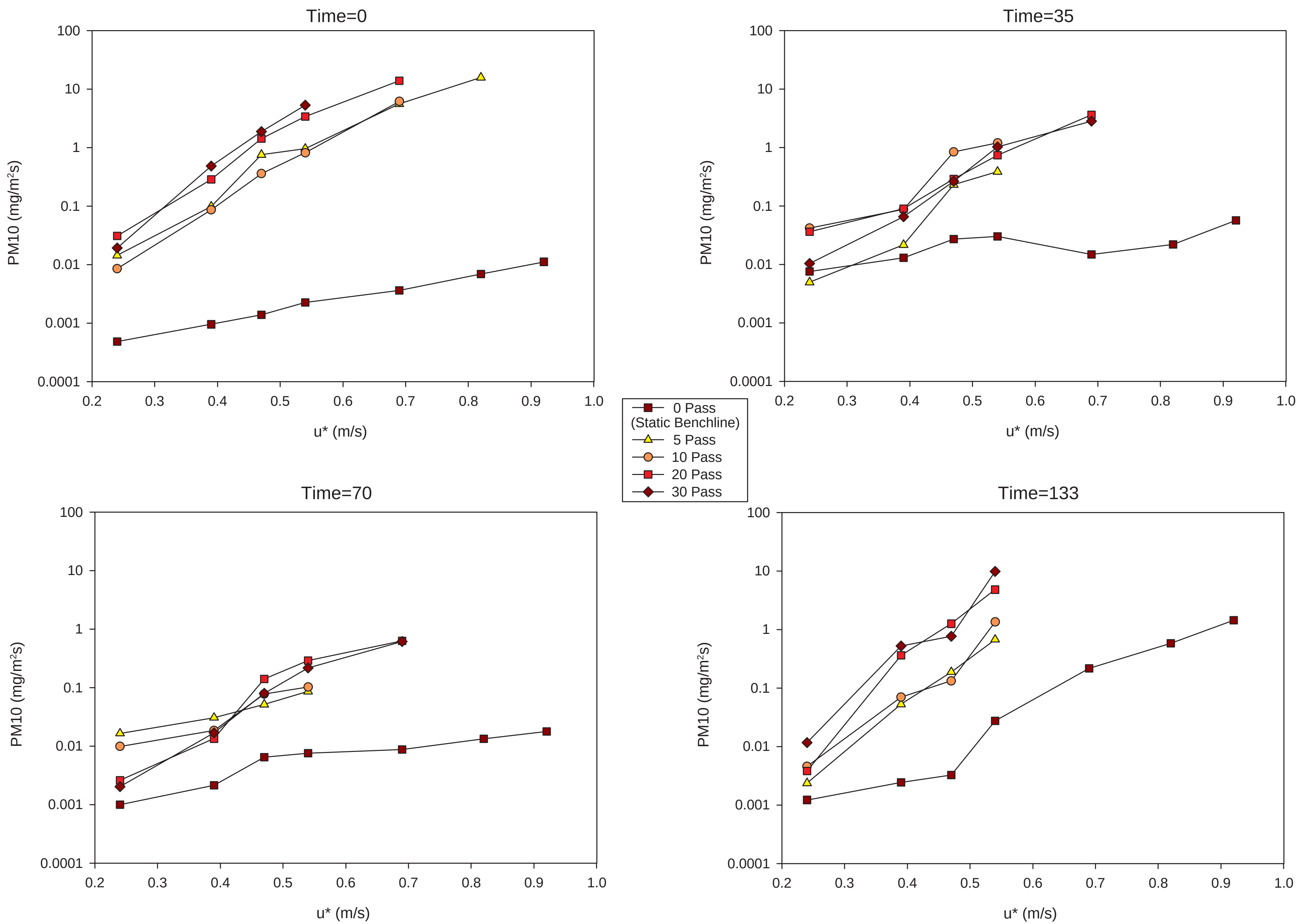
FIGURE 21



U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course HMMWV Surface Strength

DATE: 06-09-09

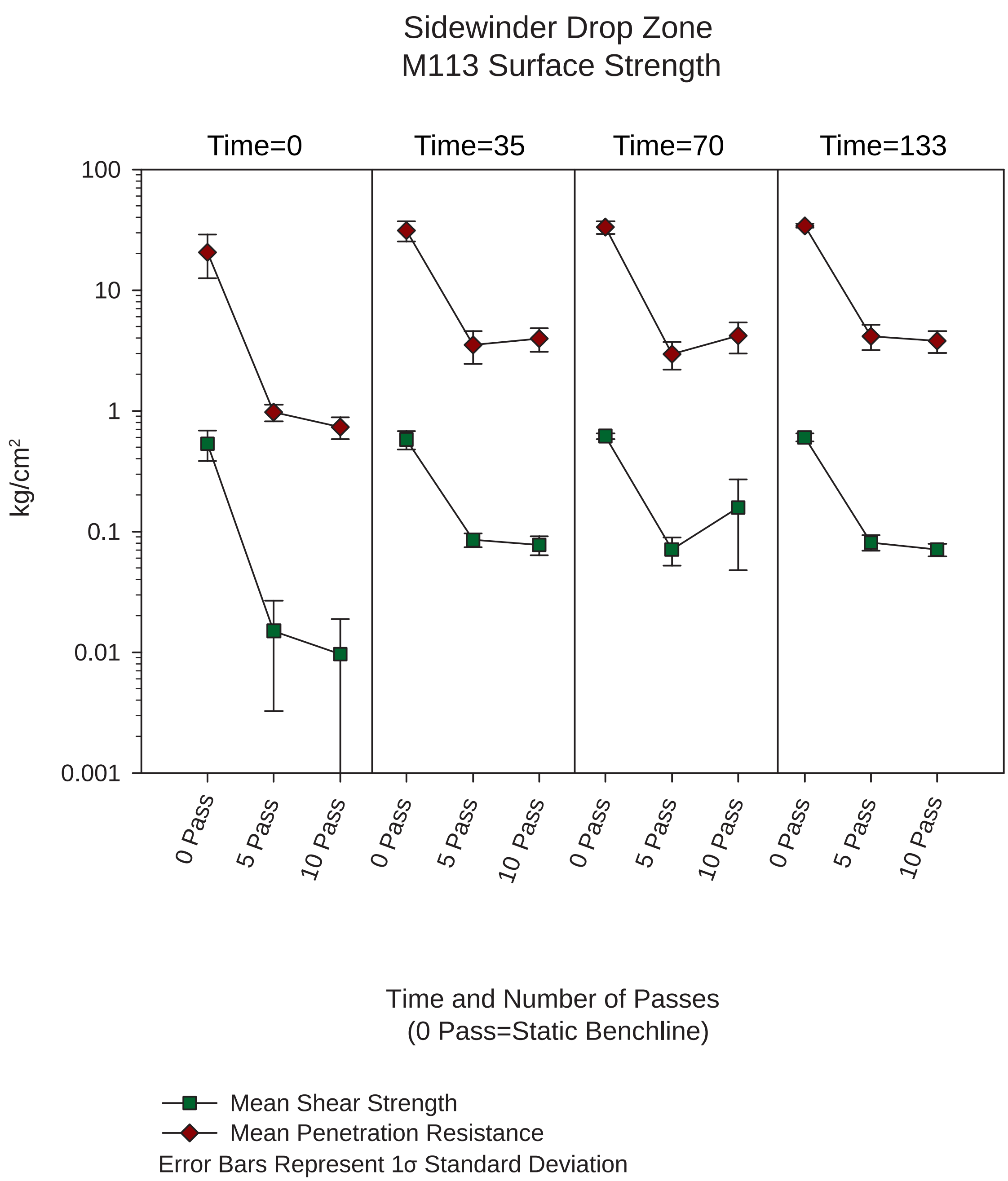
FIGURE 22



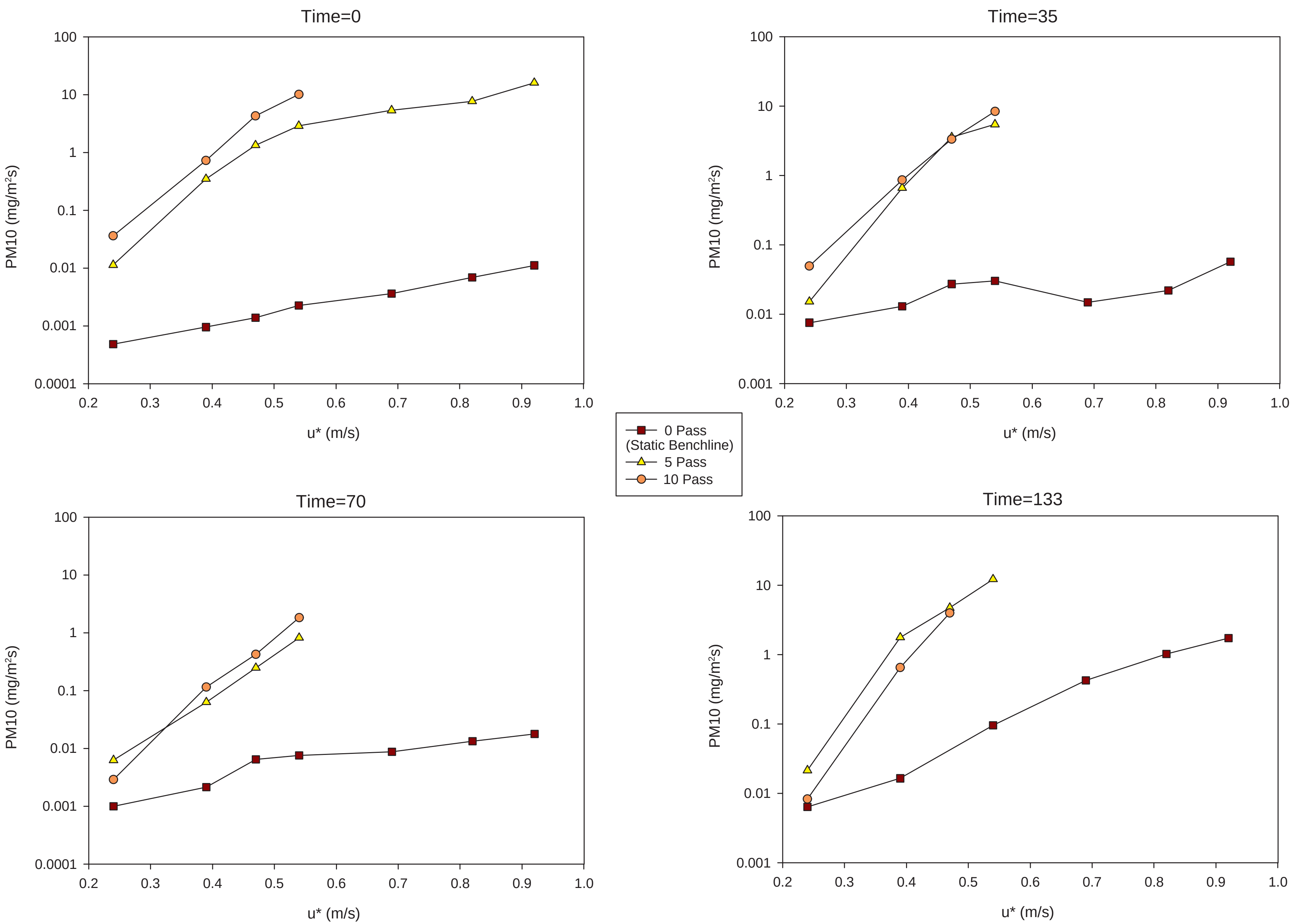
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course HMMWV PM10 Emissions

DATE: 04-01-09

FIGURE 23



Sidewinder Drop Zone
M113 Surface Strength
Time=0
Time=35
Time=70
Time=133
100
10
1
0.1
0.01
0.001
kg/cm2
0 Pass
5 Pass
10 Pass
0 Pass
5 Pass
10 Pass
0 Pass
5 Pass
10 Pass
0 Pass
5 Pass
10 Pass
Time and Number of Passes
(0 Pass=Static Benchline)
Mean Shear Strength
Mean Penetration Resistance
Error Bars Represent 1σ Standard Deviation

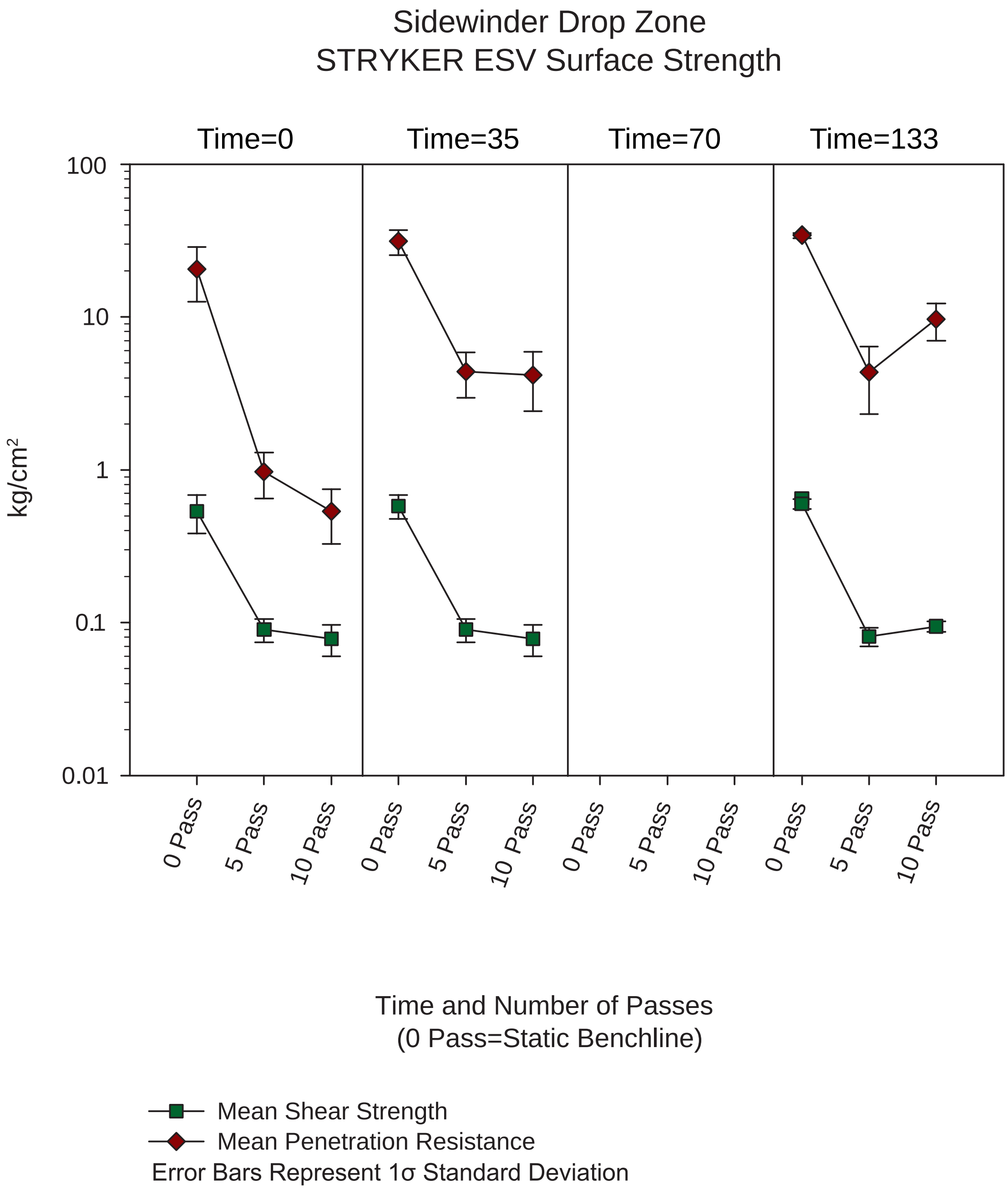


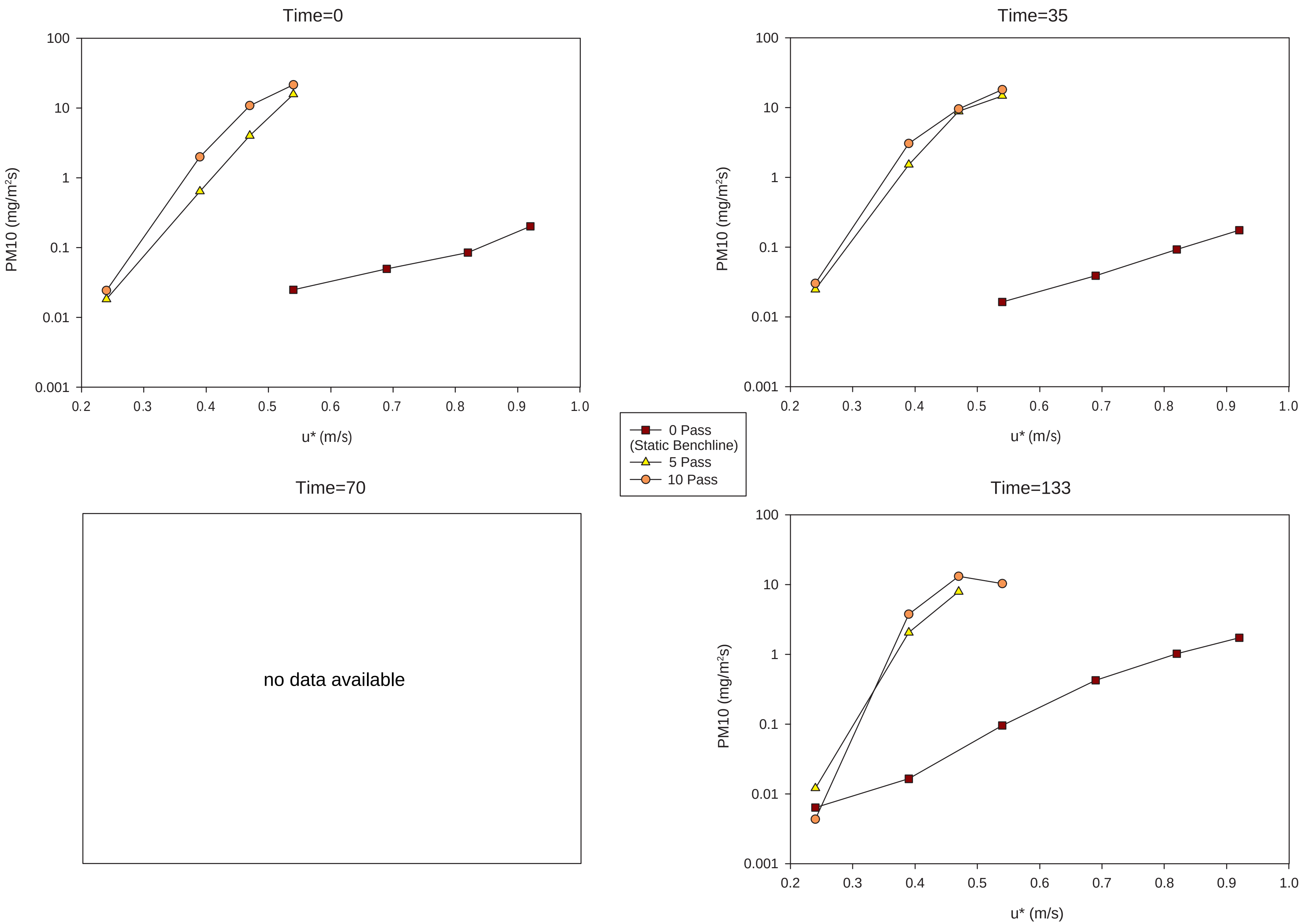
Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone M113 PM10 Emissions

DATE: 04-01-09

FIGURE 25


Sidewinder Drop Zone
STRYKER ESV Surface Strength
Time=0
Time=35
Time=70
Time=133
100
10
1
0.1
0.01
kg/cm2
0 Pass
5 Pass
10 Pass
0 Pass
5 Pass
10 Pass
0 Pass
5 Pass
10 Pass
0 Pass
5 Pass
10 Pass
Time and Number of Passes
(0 Pass=Static Benchline)
Mean Shear Strength
Mean Penetration Resistance
Error Bars Represent 1σ Standard Deviation

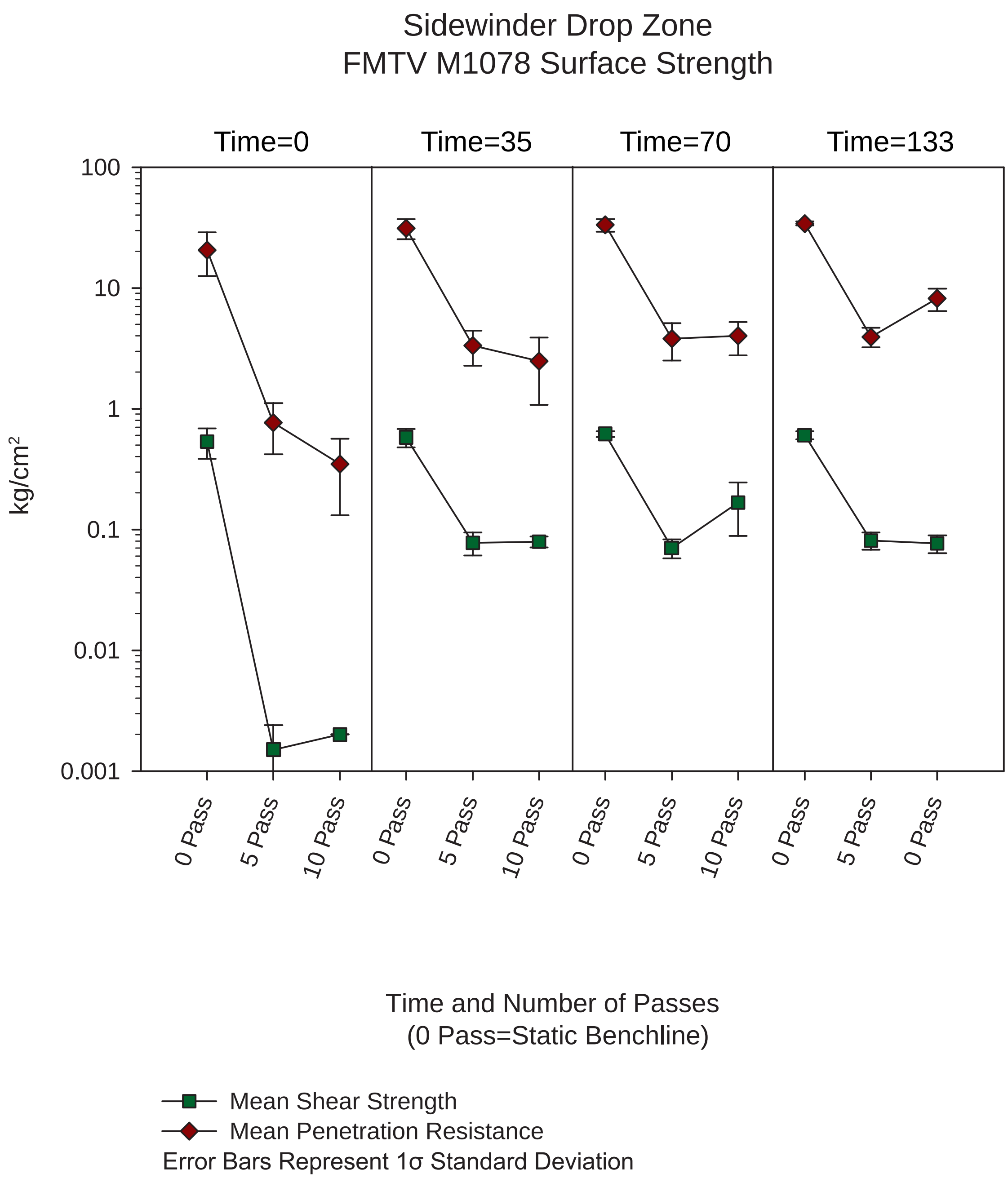


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone STRYKER ESV PM10 Emissions

DATE: 04-01-09

FIGURE 27

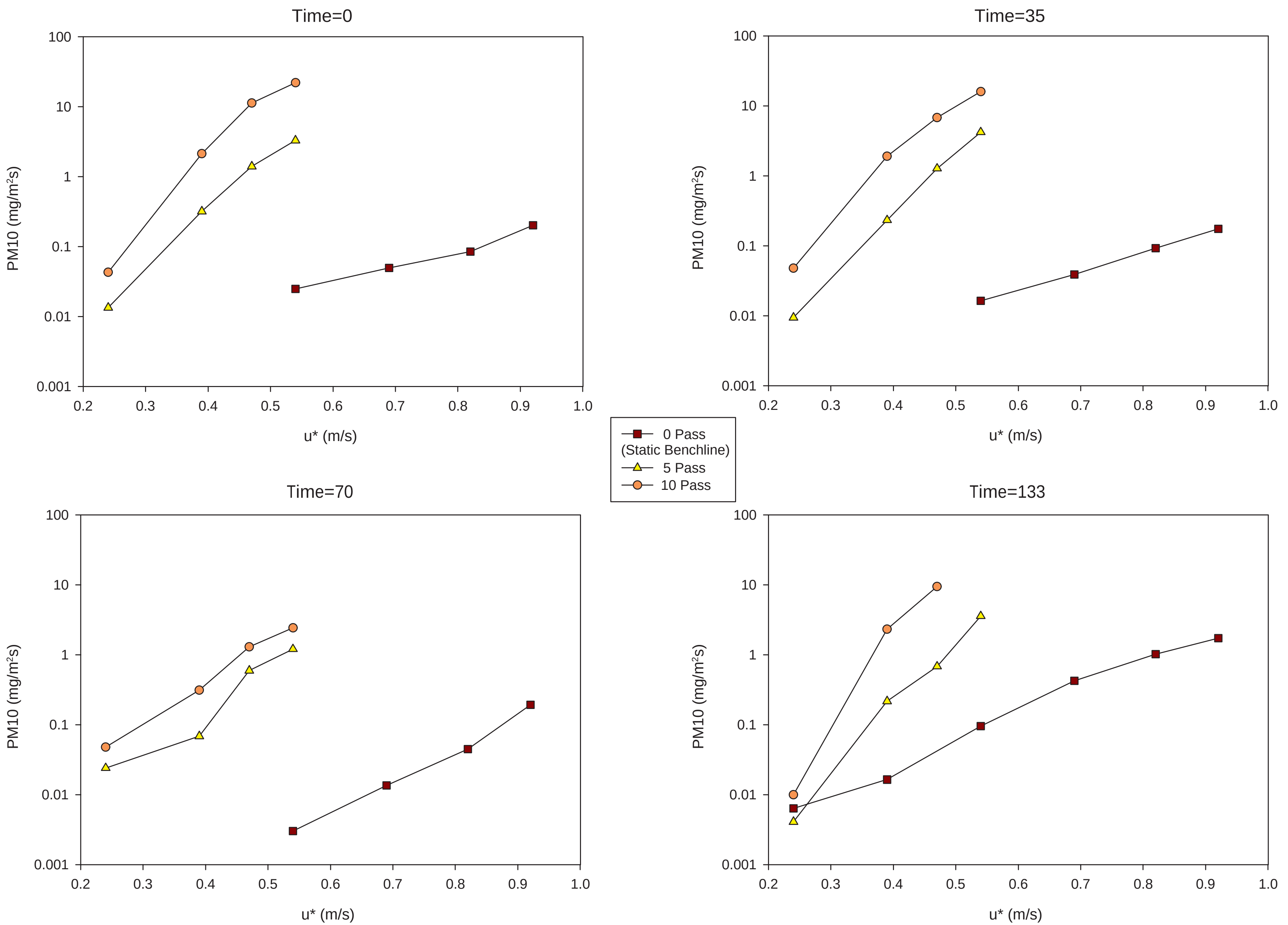


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Sidewinder Drop Zone FMTV M1078 Surface Strength

DATE: 06-09-09

FIGURE 28

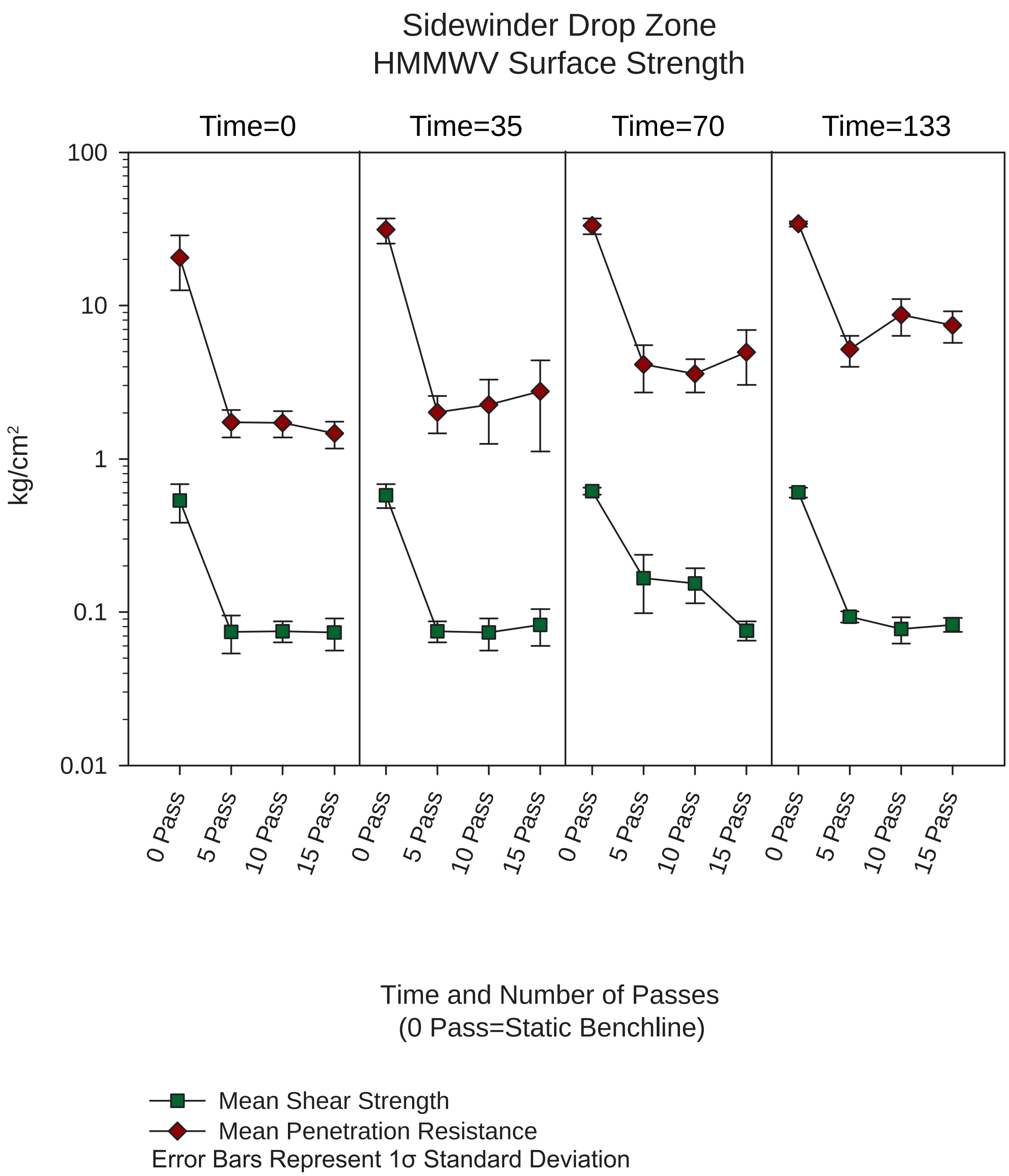


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone FMTV M1078 PM10 Emissions

DATE: 04-01-09

FIGURE 29

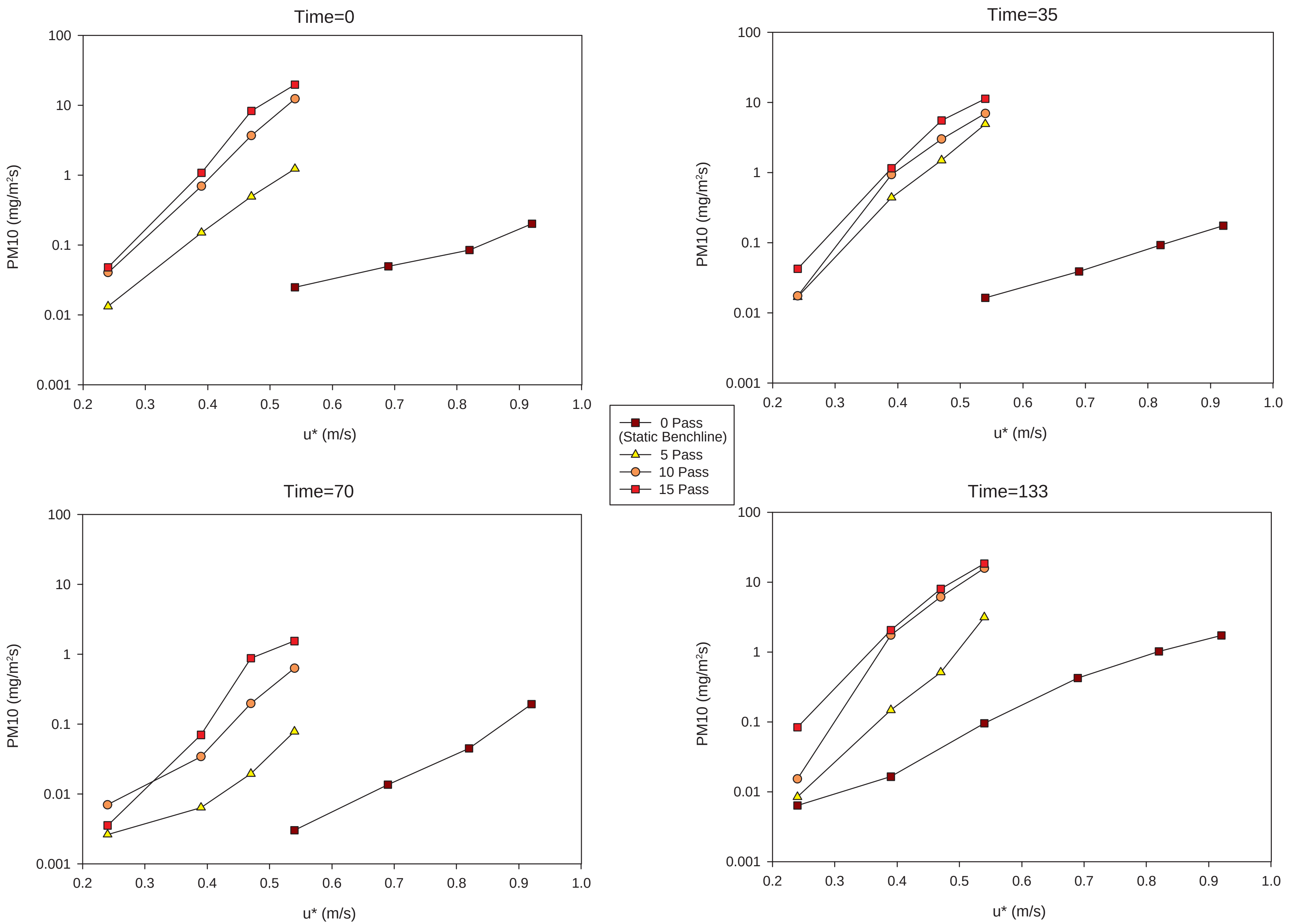


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Sidewinder Drop Zone HMMWV Surface Strength

DATE: 06-09-09

FIGURE 30

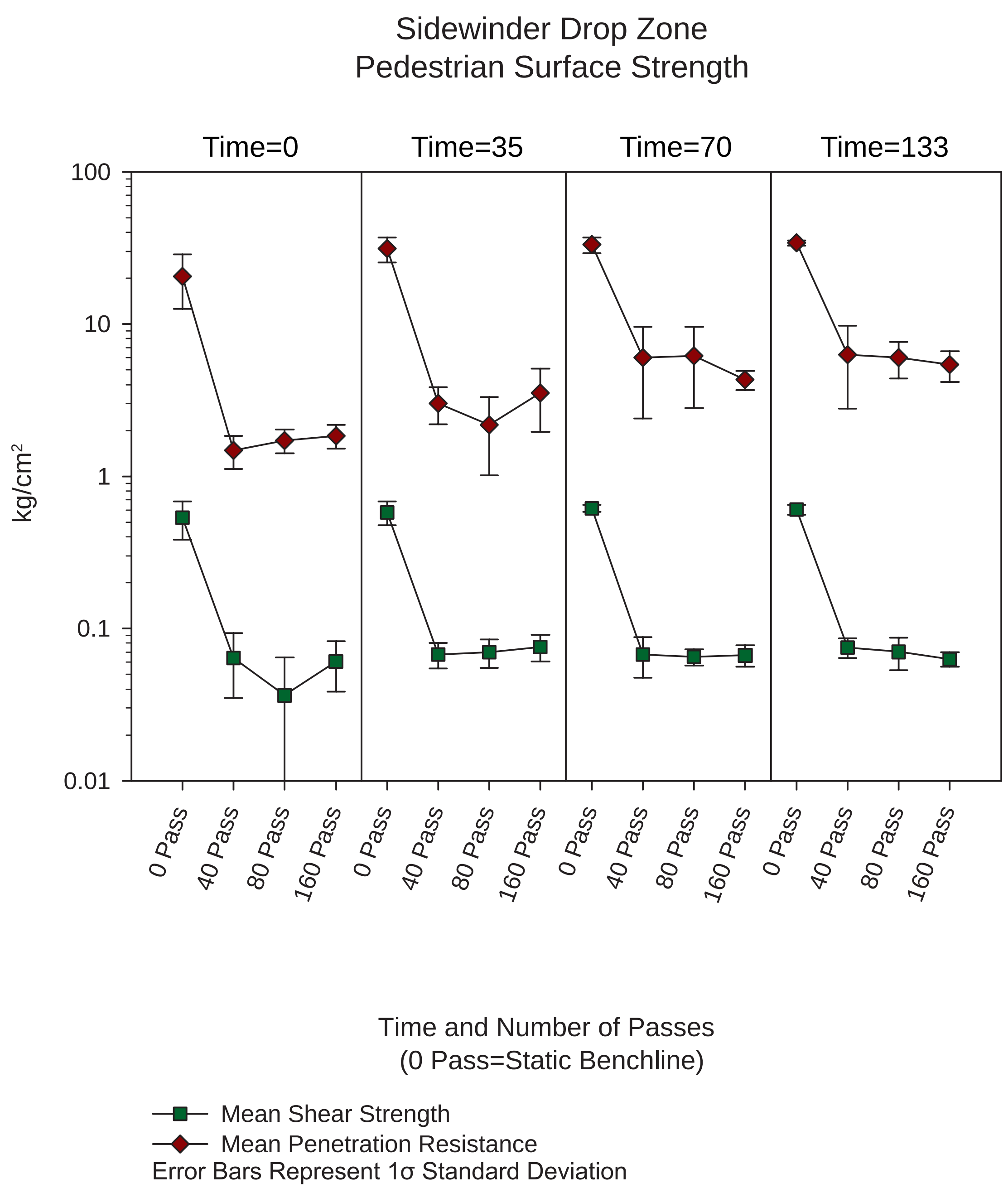


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone HMMWV PM10 Emissions

DATE: 04-01-09

FIGURE 31

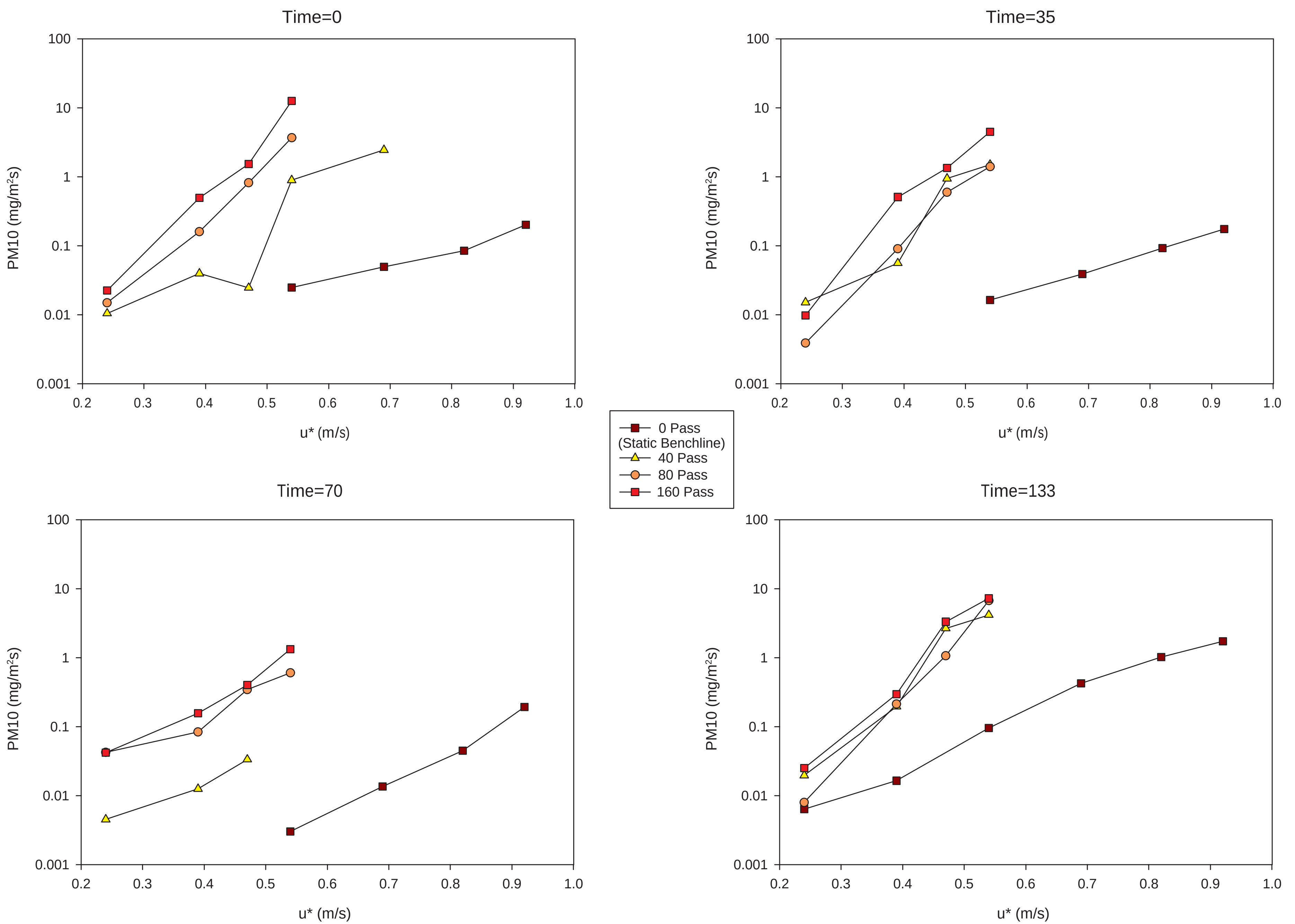


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Pedestrian Surface Strength

DATE: 06-09-09

FIGURE 32

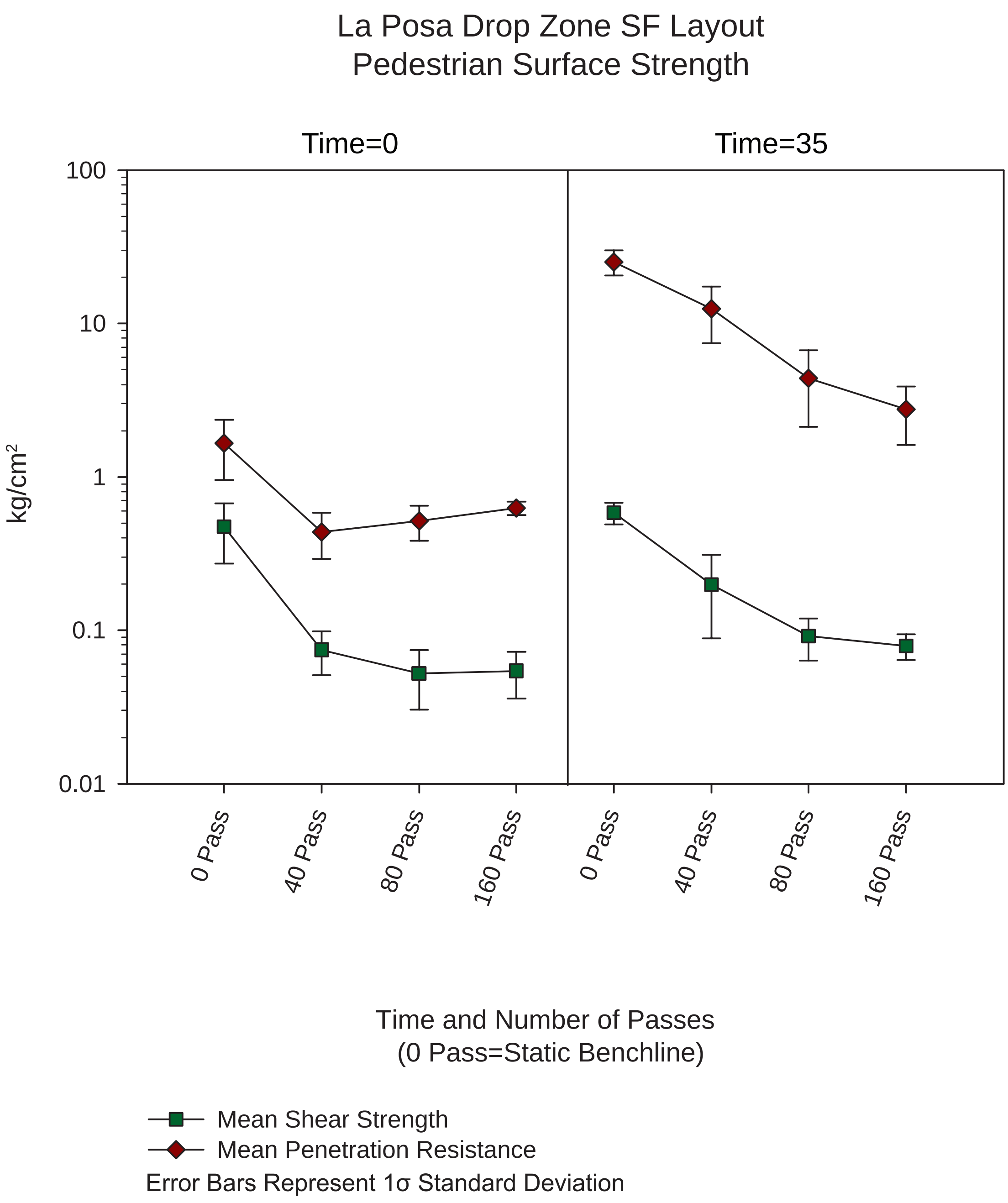


Desert Research Institute

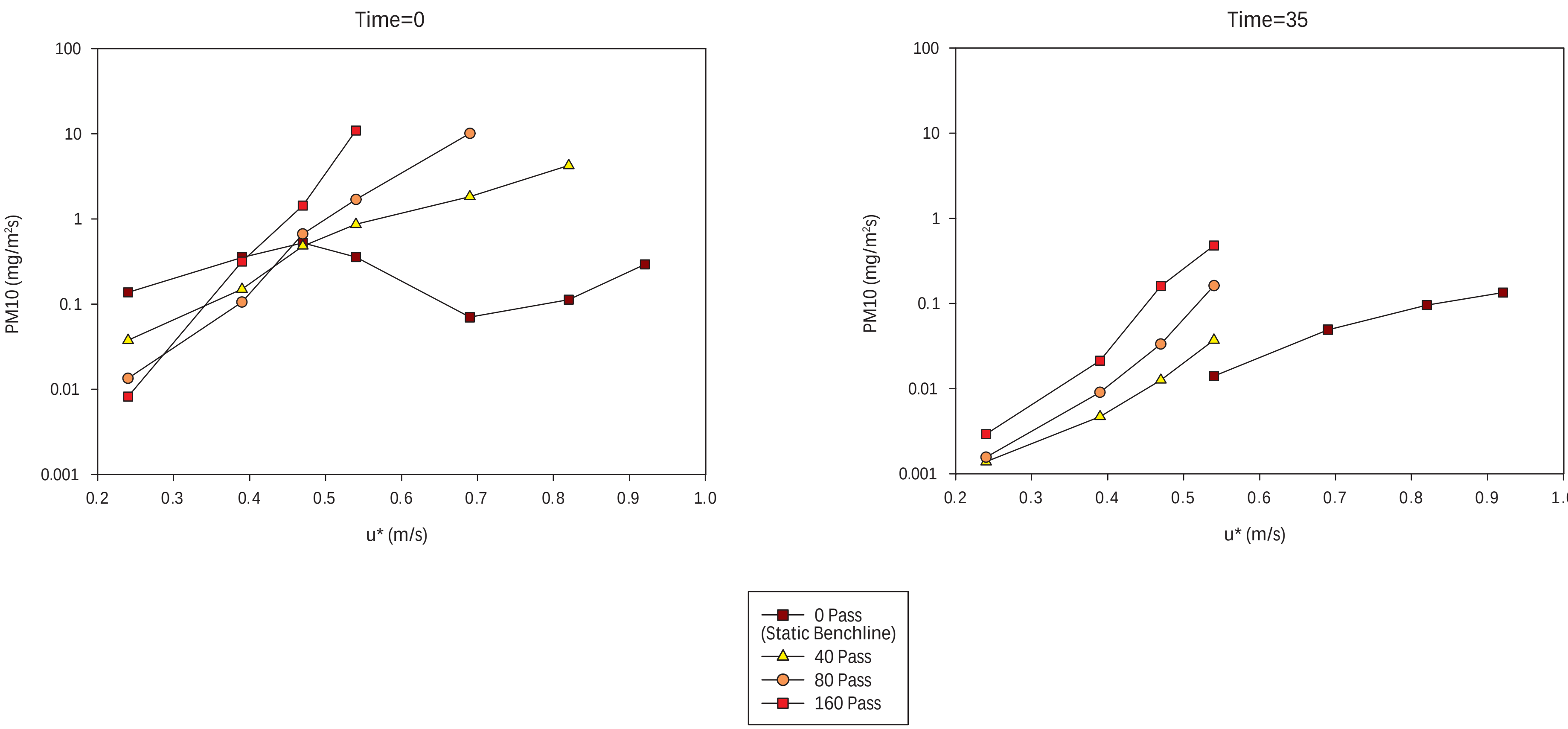
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Pedestrian PM10 Emissions

DATE: 04-01-09

FIGURE 33



Desert Research Institute	**U.S. ARMY YUMA PROVING GROUND** **DUST SUPPRESSANT TESTING** **La Posa Drop Zone SF Layout**	DATE: 04-01-09 FIGURE 34



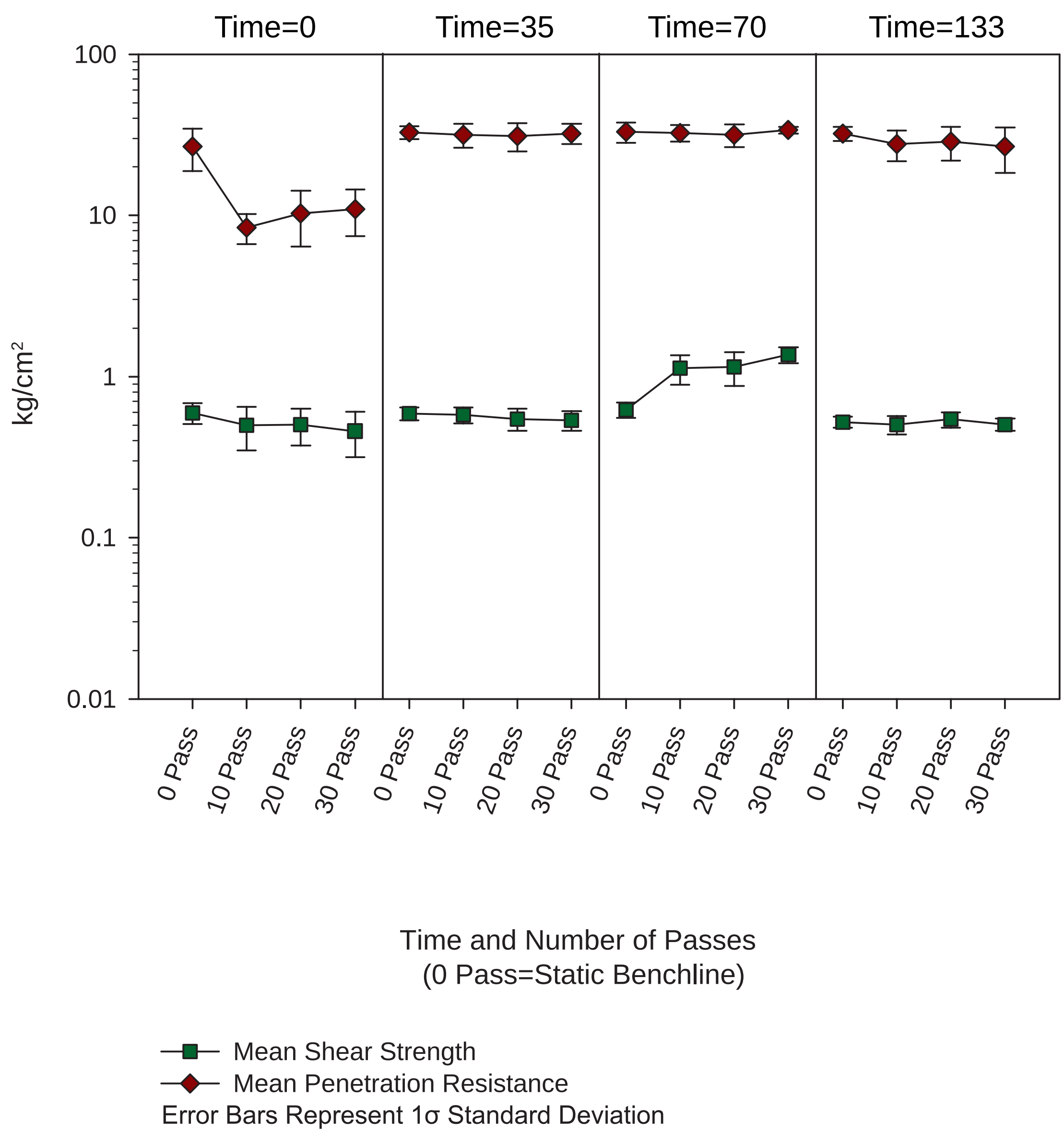
DRI Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone SF Layout Pedestrian PM10 Emissions

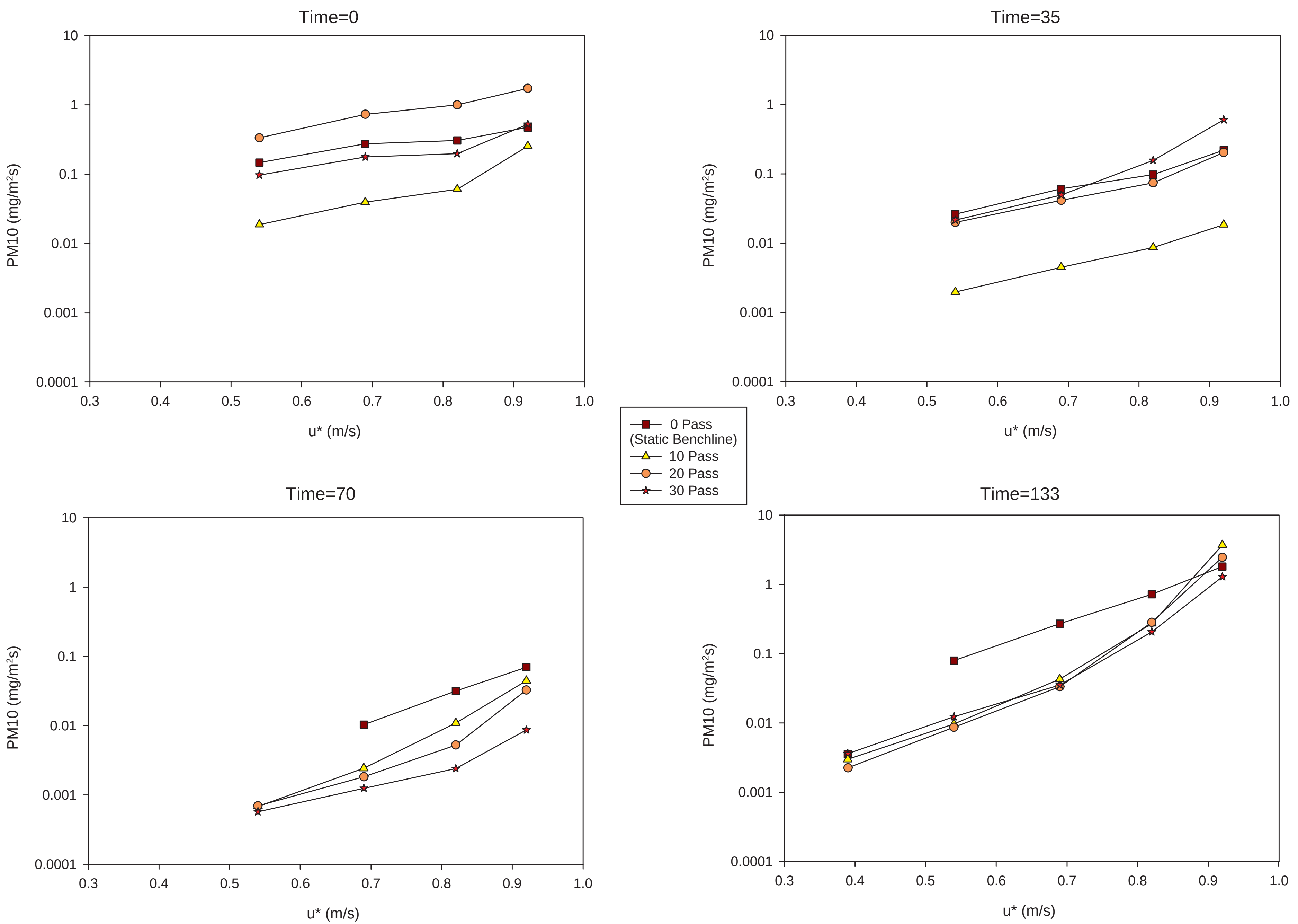
DATE: 04-01-09

FIGURE 35

Sidewinder Drop Zone Rotorcraft Layout
Bell UH-1 Surface Strength



	U.S. ARMY YUMA PROVING GROUND **DUST SUPPRESSANT TESTING** **Sidewinder Drop Zone Rotorcraft Layout Bell UH-1 Surface Strength**	DATE: 06-09-09 FIGURE 36

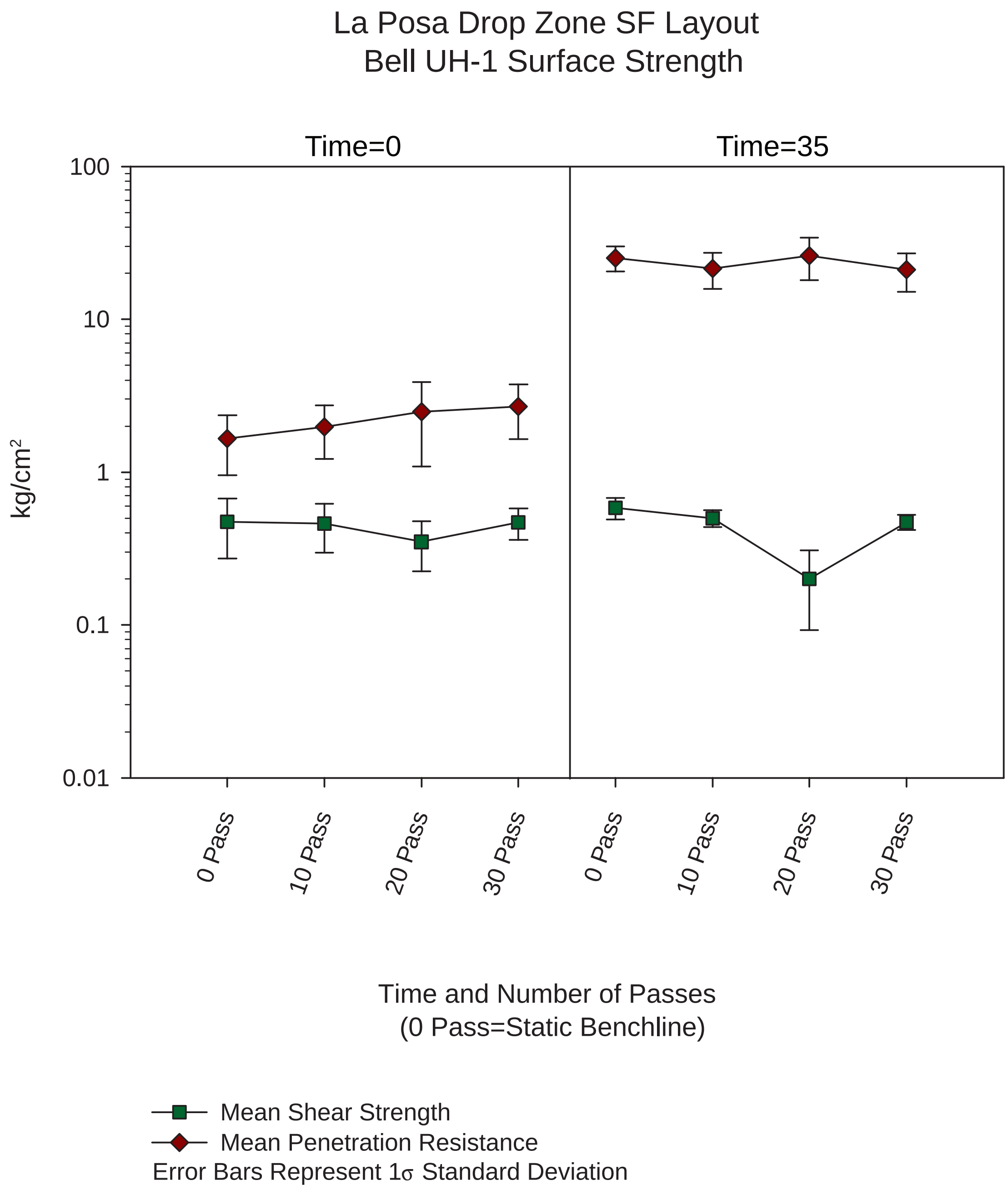


Desert Research Institute

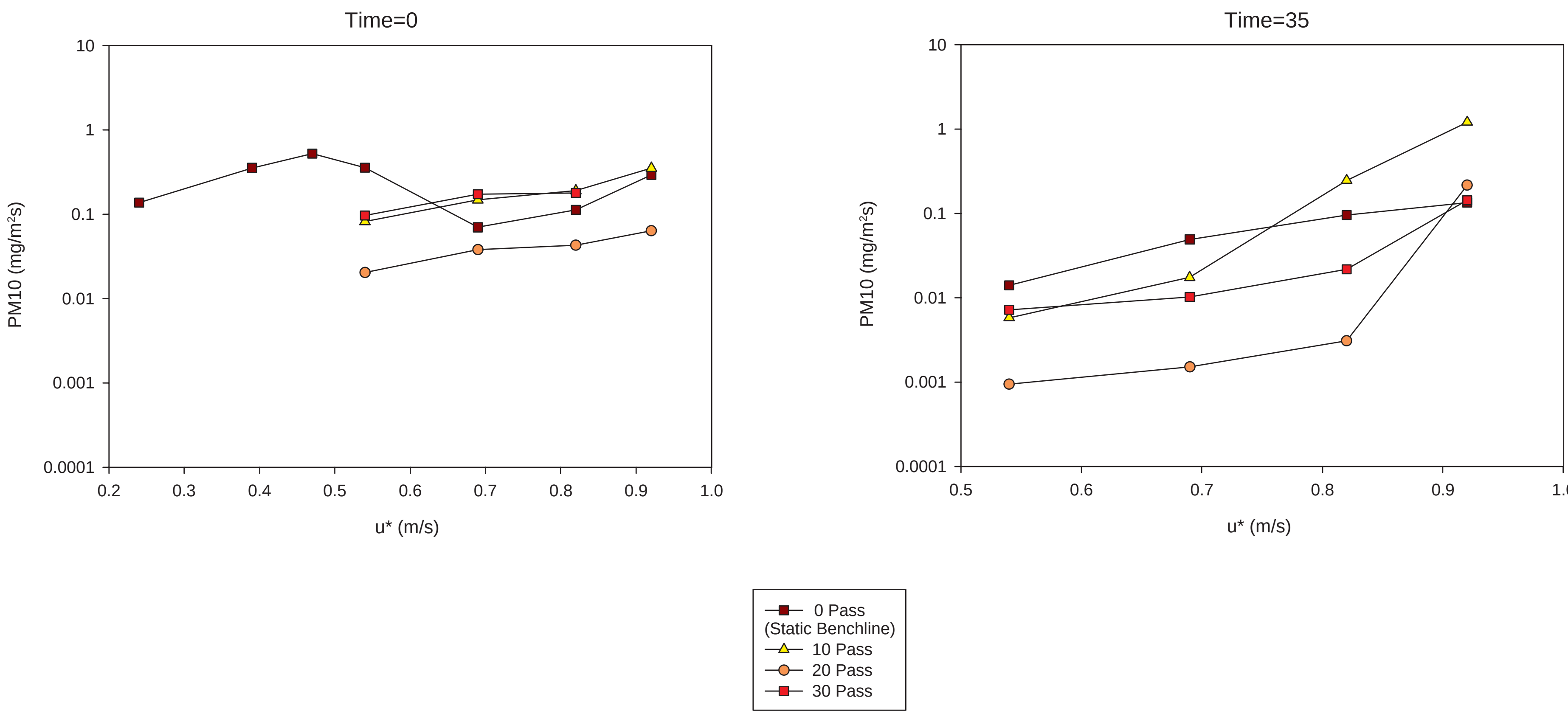
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Bell UH-1 PM10 Emissions

DATE: 04-01-09

FIGURE 37



Desert Research Institute	**U.S. ARMY YUMA PROVING GROUND** **DUST SUPPRESSANT TESTING** **La Posa Drop Zone SF Layout**	DATE: 04-01-09 FIGURE 38

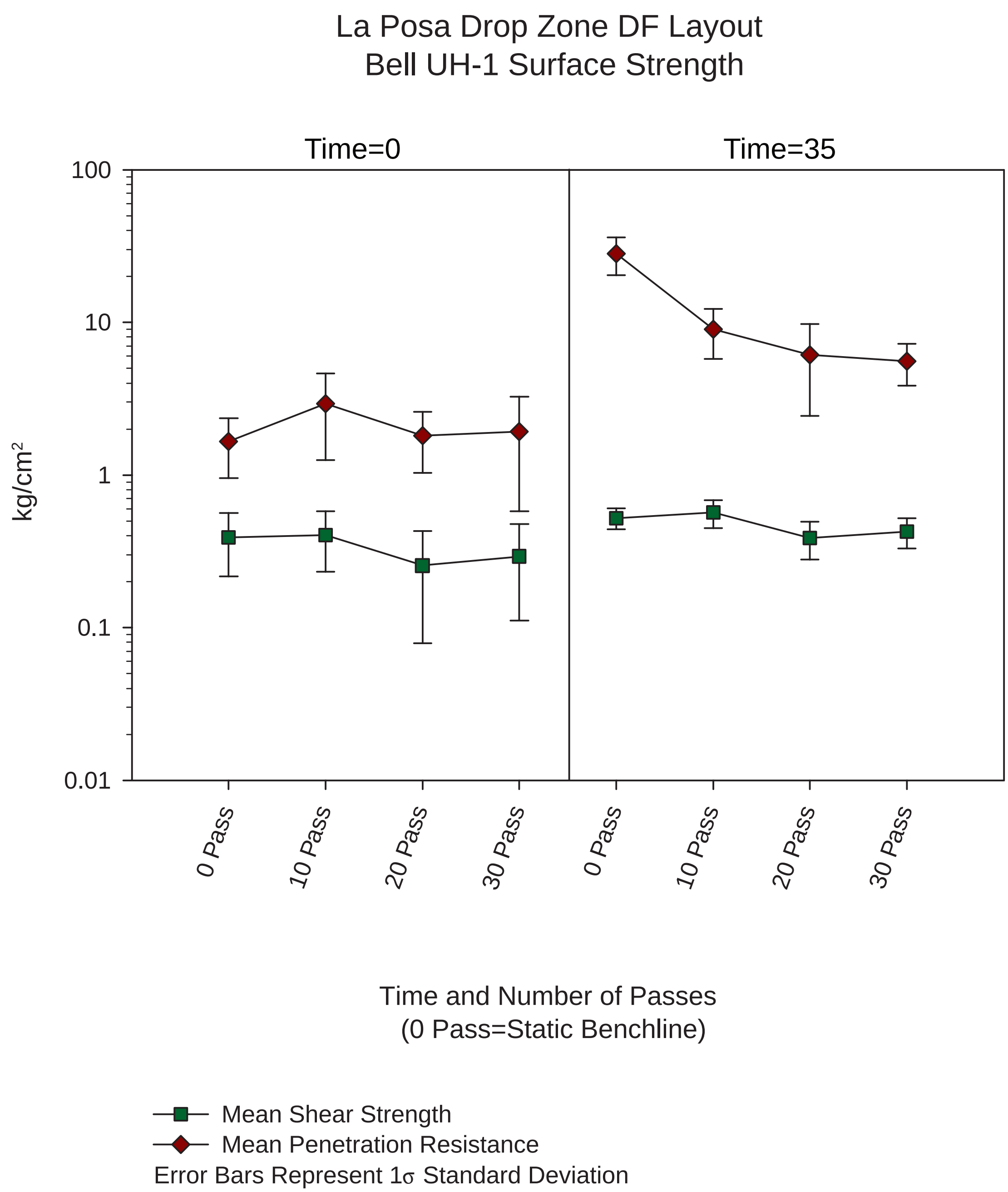


DRI Desert Research Institute

U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone SF Layout Bell UH-1 PM10 Emissions

DATE: 04-01-09

FIGURE 39

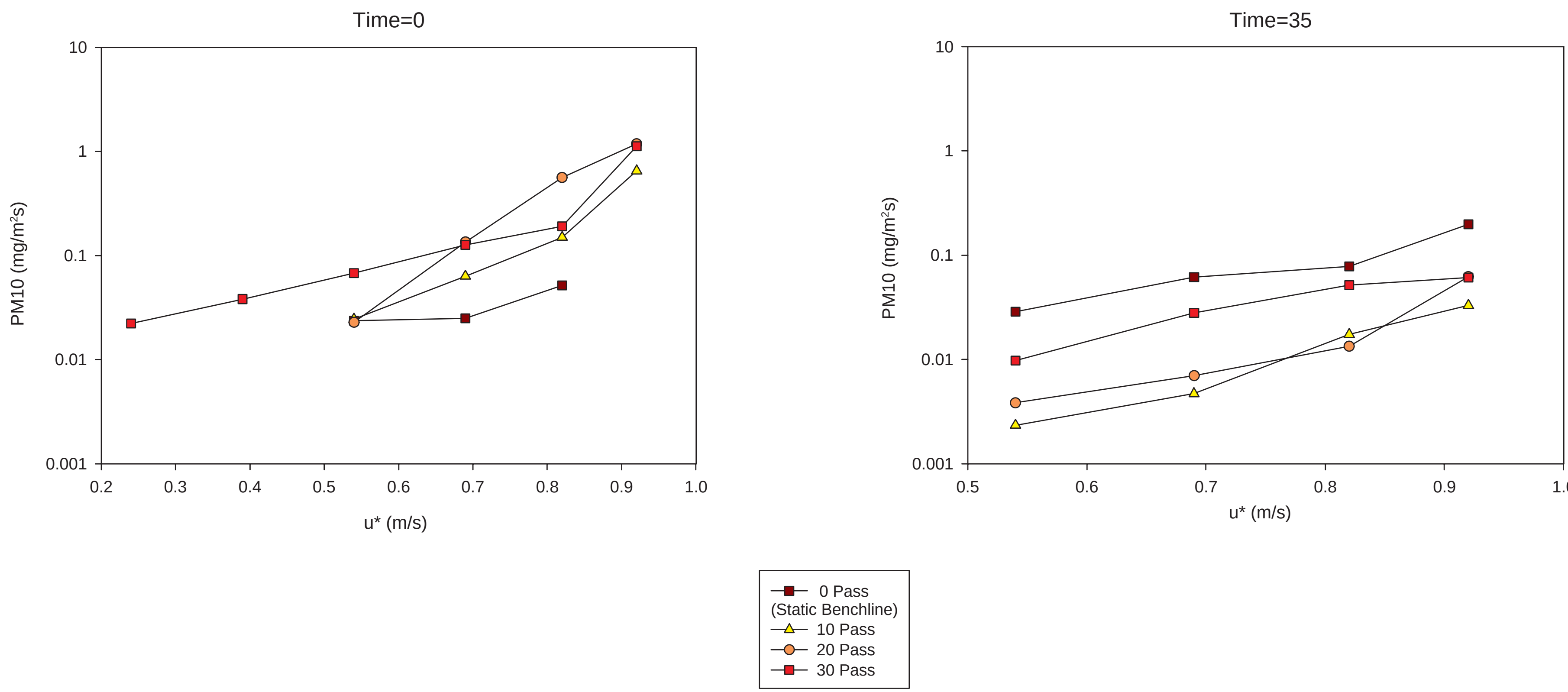


Desert Research Institute

U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
La Posa Drop Zone DF Layout

DATE: 04-01-09

FIGURE 40



U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone DF Layout Bell UH-1 PM10 Emissions

DATE: 04-01-09

FIGURE 41

8.0 APPENDIX A – TERRALOC® MATERIAL SAFETY DATA SHEETS (MSDS) AND CERTIFICATE OF TOXICITY OF TERRALOC 16 (7:1 DILUTION)

MATERIAL SAFETY DATA SHEET

Date Issued: 03/10/2006
MSDS No: TerraLOC®
Date-Revised: 04/03/2007
Revision No: 7

TerraLOC® - 8% and 16% Solution

1. PRODUCT AND COMPANY IDENTIFICATION

PRODUCT NAME: TerraLOC® - 8% and 16% Solution

MANUFACTURER

MonoSol, LLC
1701 County Line Road
Portage IN 46368
Service Number: (219) 762-3165

24 HR. EMERGENCY TELEPHONE NUMBERS

24-Hour Emergency Hotline - CHEMTREC:
From outside the U.S.: 00 +1.703.527.3887
From within the U.S.: 1.800.424.9300

2. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW

PHYSICAL APPEARANCE: Slightly viscous liquid.

IMMEDIATE CONCERNS: None

SIGNS AND SYMPTOMS OF OVEREXPOSURE

CARCINOGENICITY: Not Listed by NTP. Not Listed by IARC. Not Listed by OSHA.

ROUTES OF ENTRY: Eyes, skin, ingestion and inhalation.

3. COMPOSITION / INFORMATION ON INGREDIENTS

Chemical Name	Wt.%
Water-based non-hazardous proprietary mixture	100

4. FIRST AID MEASURES

EYES: Flush eyes with plenty of water. If irritation develops, seek medical attention.

SKIN: Remove from skin with soap and water.

INGESTION: If a large amount is ingested, seek medical attention.

INHALATION: It is advisable to wear a particle mask when working in areas with a high concentration of airborne respirable droplets.

5. FIRE FIGHTING MEASURES

FLASHPOINT AND METHOD: > (200°F) Closed Cup

EXTINGUISHING MEDIA: Water spray, carbon dioxide, dry chemical.

FIRE FIGHTING PROCEDURES: This product is a nonflammable substance. However, hazardous decomposition and combustion products may be formed in a fire situation.

6. ACCIDENTAL RELEASE MEASURES

COMMENTS: Spill response: If spilled indoors, obtain approval from local wastewater treatment plant to rinse down the drain. If spilled outside, either recover product, or flush area with water to dilute and disperse. If in an area where you do not desire dust control, absorb material and dispose of according to local, state, and federal regulations.

7. HANDLING AND STORAGE

GENERAL PROCEDURES: Read MSDS before using this product.

STORAGE: Avoid freezing. If possible, store at room temperature.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

PERSONAL PROTECTIVE EQUIPMENT

EYES AND FACE: Although this product is non-hazardous, it is safe practice to wear safety glasses and a particulate mask when working around a high concentration of airborne droplets.

SKIN: Gloves are not required under normal conditions. Take into consideration how the product is being used and hazards associated with other materials used in conjunction with this product.

9. PHYSICAL AND CHEMICAL PROPERTIES

PHYSICAL STATE: Liquid

ODOR: Slight fatty odor.

COLOR: Colorless or slightly yellow

pH: 7-8

FLASHPOINT AND METHOD: > (200°F) Closed Cup

SOLUBILITY IN WATER: Infinitely soluble

SPECIFIC GRAVITY: 1.05 g/cc

COMMENTS: VOC content: <10 ppm (<0.001%)

10. STABILITY AND REACTIVITY

STABILITY: The product is stable under normal ambient conditions of temperature and pressure.

POLYMERIZATION: Will not occur

CONDITIONS TO AVOID: Temperatures above 200° C (392° F).

HAZARDOUS DECOMPOSITION PRODUCTS: Irritating and toxic fumes at elevated temperatures from burning, heating or reaction with other materials.

INCOMPATIBLE MATERIALS: Oxidizing agents (i.e. perchlorates, nitrates etc.)

11. TOXICOLOGICAL INFORMATION

EYE EFFECTS: Information representative of the major component indicates that the powder and aqueous solutions are slightly irritating to rabbit eyes, irritation subsided by 48 hours after exposure.

SKIN EFFECTS: In powder form the major component, polyvinyl alcohol, was nonirritating to rabbit skin. In aqueous solution, slight irritation to rabbit skin was noted. Not a skin sensitizer in guinea pigs when dosed as a 10% aqueous solution.

CARCINOGENICITY

Notes: Not listed by IARC, NTP, or OSHA as a carcinogen.

12. ECOLOGICAL INFORMATION

COMMENTS: The acute exposure results for biological acute toxicity at a typical 8:1 dilution is as follows:
Earthworm: 7-day LC50 >10,000 mg/L 14-day LC50 >10,000 mg/L
Daphnia magna: 24-hr EC50 >8,000 mg/L 48-hr EC50 2,732 mg/L 48-hr NOEC 2,000 mg/L
Fathead minnow: 48-hr LC50 4,925 mg/L 96-hr NOEC 4,000 mg/L
Green Alga P. Subcapita: 72-hr LC50 190 mg/L 72-hr NOEC 75 mg/L

13. DISPOSAL CONSIDERATIONS

DISPOSAL METHOD: Product is water-soluble and non-hazardous. Product is normally accepted by local wastewater treatment plants. Obtain prior approval before disposal. For large quantities: reclaim, dilute and disperse (if in dust suppressant application area), or absorb and place in waste containers for disposal.

14. TRANSPORT INFORMATION

COMMENTS: Not regulated by DOT, IATA, IMDG, or ADR.

15. REGULATORY INFORMATION

UNITED STATES

SARA TITLE III (SUPERFUND AMENDMENTS AND REAUTHORIZATION ACT)

FIRE: No **PRESSURE GENERATING:** No **REACTIVITY:** No **ACUTE:** No **CHRONIC:** No

TSCA (TOXIC SUBSTANCE CONTROL ACT)

TSCA REGULATORY: We certify that all components are either on the TSCA inventory or qualify for an exemption.

16. OTHER INFORMATION

REASON FOR ISSUE: revision

APPROVED BY: Andrew Verrall **TITLE:** Director of Research & Development

PREPARED BY: Melanie C. Kroczek, CHMM

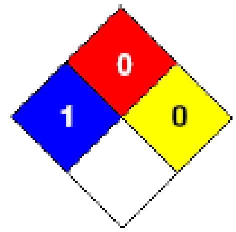
INFORMATION CONTACT: Melanie C. Kroczek

REVISION SUMMARY: Revision #: 7 This MSDS replaces the January 22, 2007 MSDS. Any changes in information are as follows: In Section 9 Comments

HMIS RATING

HEALTH:	1
FLAMMABILITY:	0
PHYSICAL HAZARD:	0
PERSONAL PROTECTION:	B

NFPA CODES



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www.abclabs.com

abc Laboratories

7200 E. ABC Lane, Columbia, MO 65202 • Tel: 573/443-9000 Fax: 573/443-9033

CERTIFICATION OF TOXICITY OF TERRALOC 16 (7:1 DILUTION)

The following toxicity data were generated by studies performed at ABC Laboratories, Inc. following test methods described by the Organisation for Economic Co-operation and Development (OECD) and the appropriate Good Laboratory Practices.

Species Information	EC_{50}	No-observable Effect Concentration (NOEC)
Daphnia magna – 48 hour	2,700 mg/L	2,000 mg/L
Fathead minnow, *Pimephales promelas* – 96 hour	4,600 mg/L	4,000 mg/L
Green Alga, *Pseudokirchneriella subcapitata* – 72 hour	190 mg/L	75 mg/L
Earthworm, *Eisenia fetida* – 14 day	>10,000 mg/kg	10,000 mg/kg

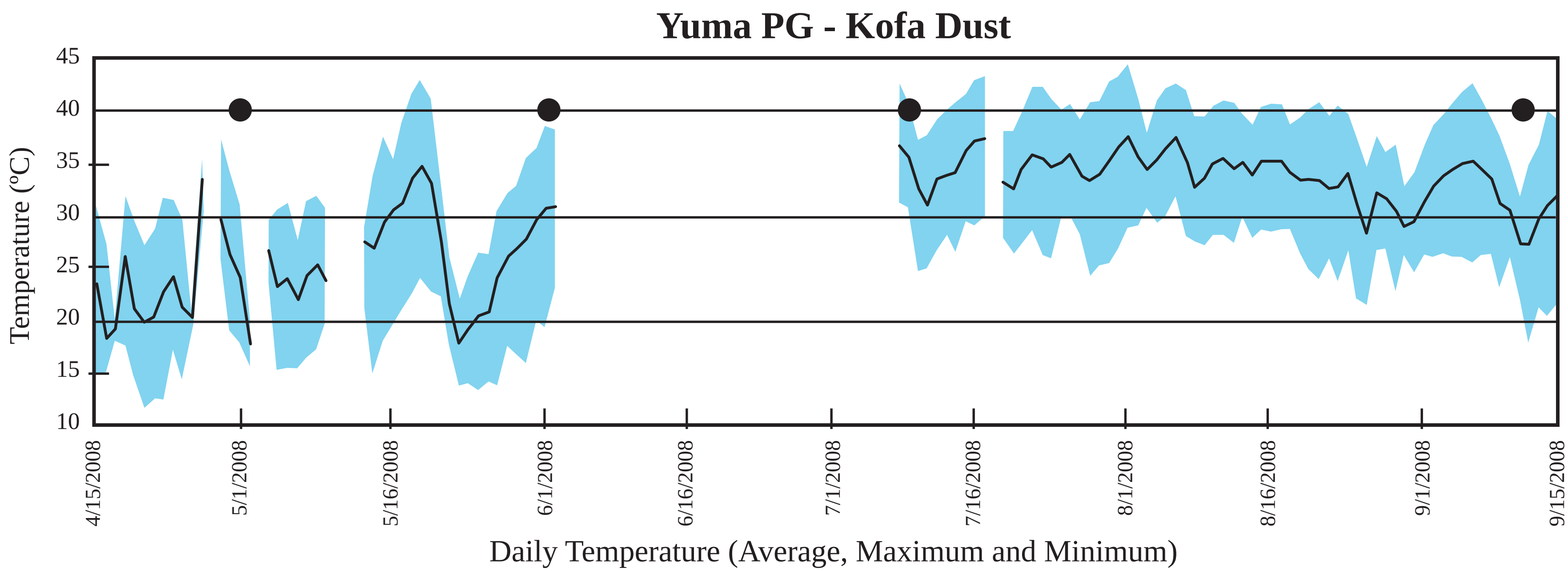
The median effective concentration (EC_{50}) and the no-observable effect concentration values reported above are based upon nominal concentrations of TerraLOC 16 in a typical 7:1 dilution with water.

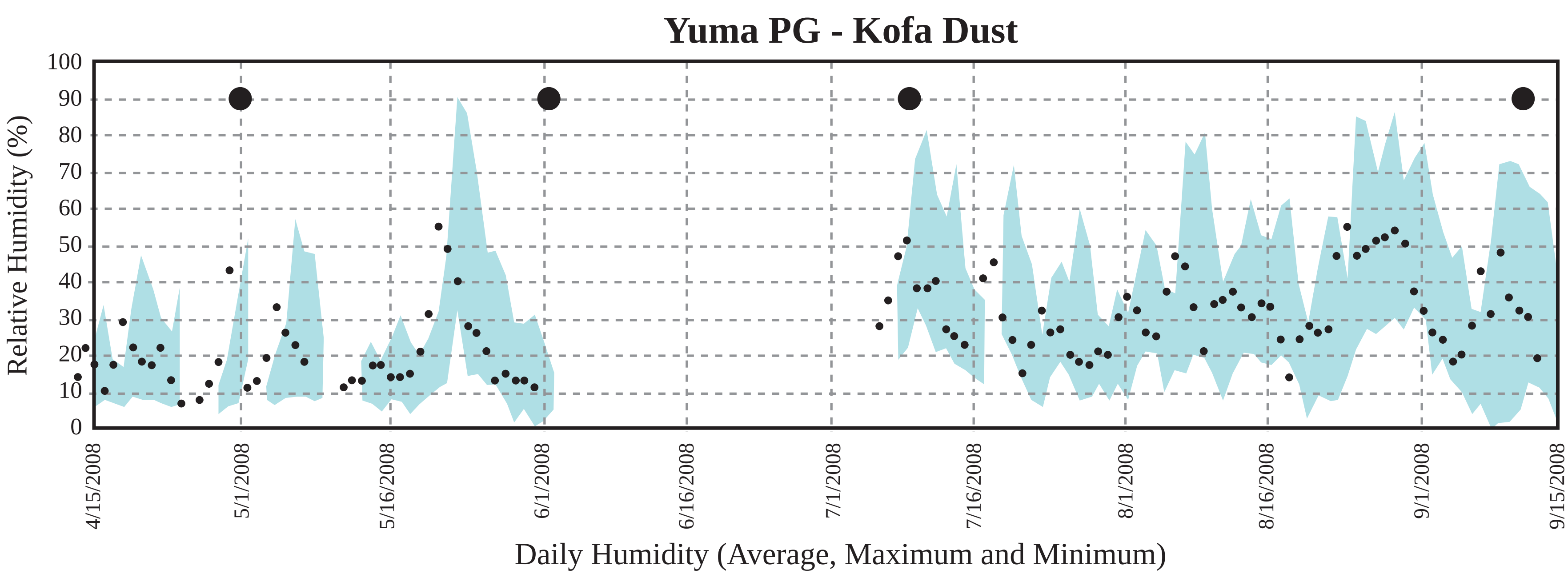
Based upon the calculated EC_{50} values of >100 mg/L, TerraLOC 16 can be categorically classified as practically non-toxic to aquatic and terrestrial organisms (U.S. EPA Hazard Evaluation Division, Standard Evaluation Procedure EPA-540/9-851-006).

John Aufderheide
Senior Toxicologist, Group Leader
ABC Laboratories, Inc.

01 May 08
Date

8.0 APPENDIX B – METEOROLOGY GRAPHICS



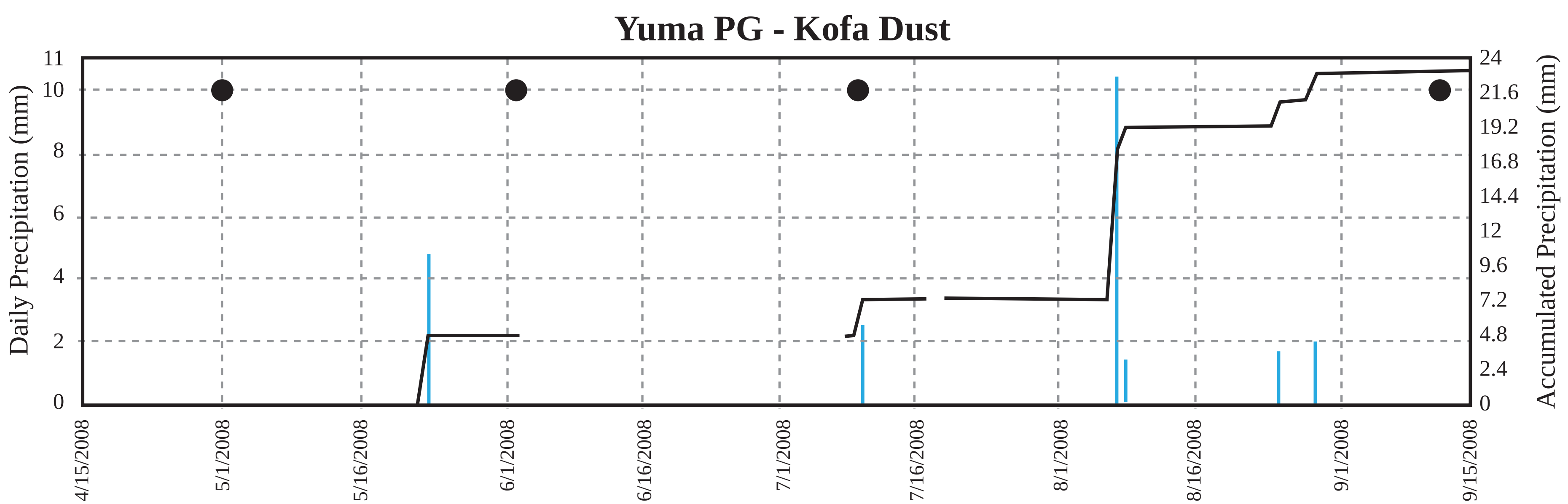


DRI Desert Research Institute

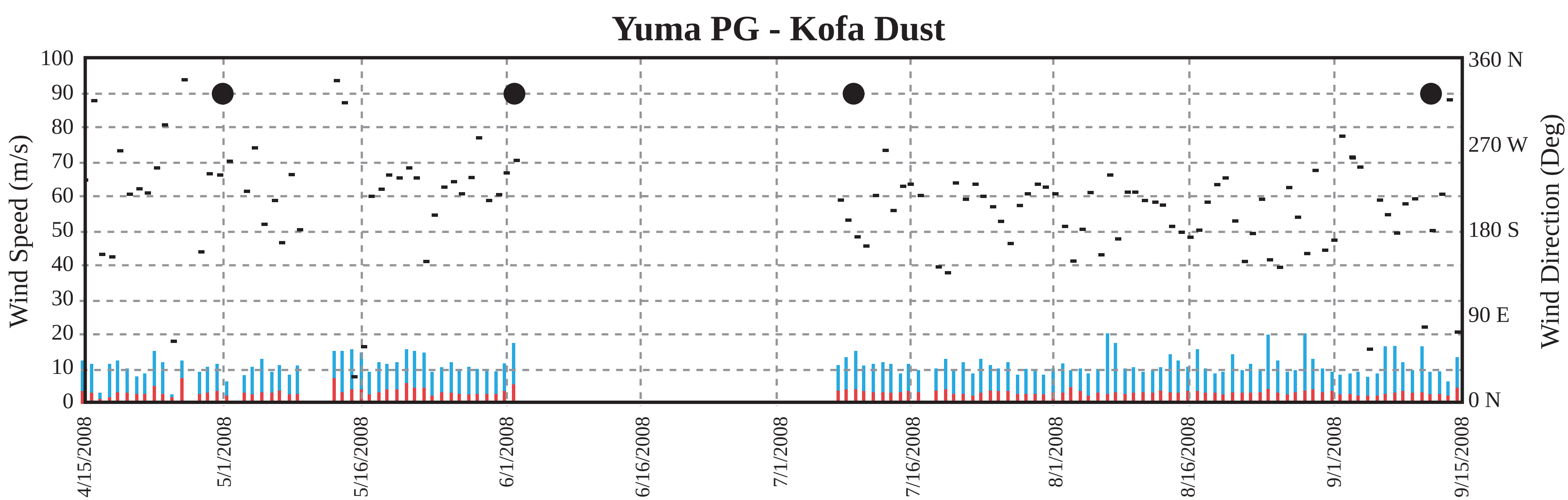
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course Proxy Temperature and Humidity

DATE: 2-2-09

FIGURE A-1



Precipitation (Accumulated and Daily total)



Wind Speed (Ave/red and Gust/blue) and Direction

Desert Research Institute

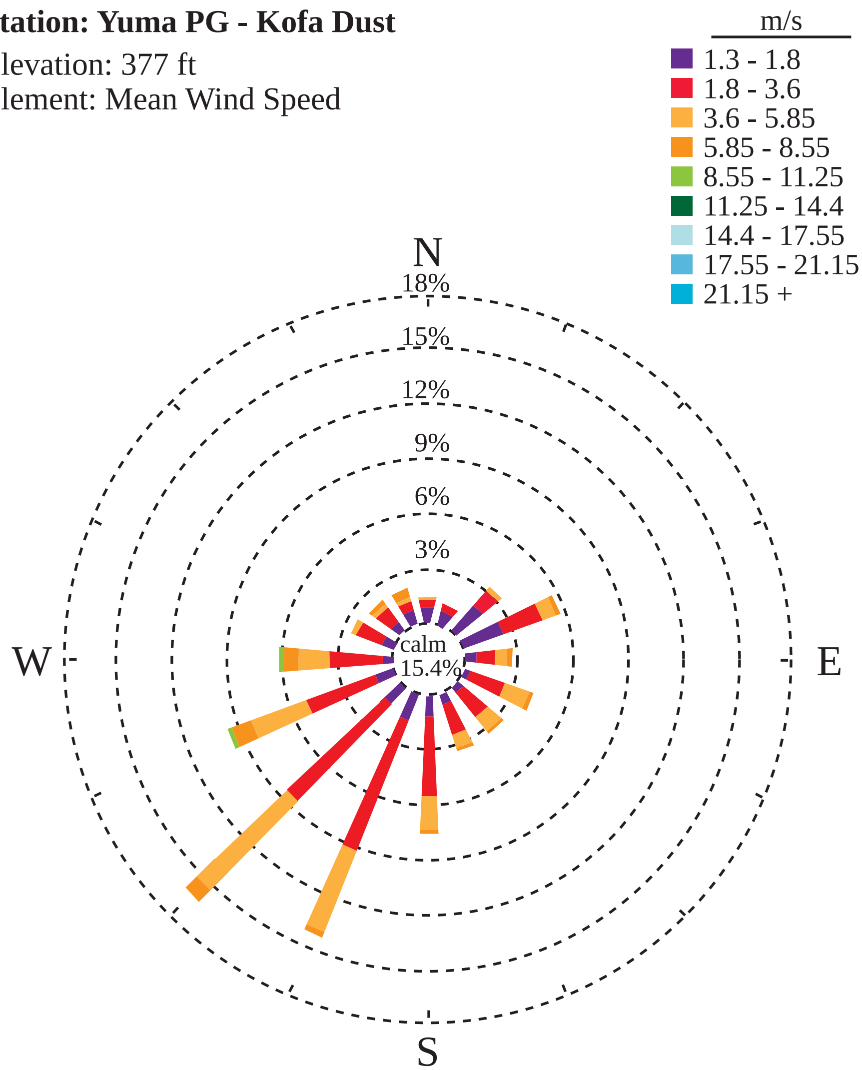
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Muggins Mesa Dust Course Proxy Precipitation and Wind Speed

DATE: 2-2-09

FIGURE A-2

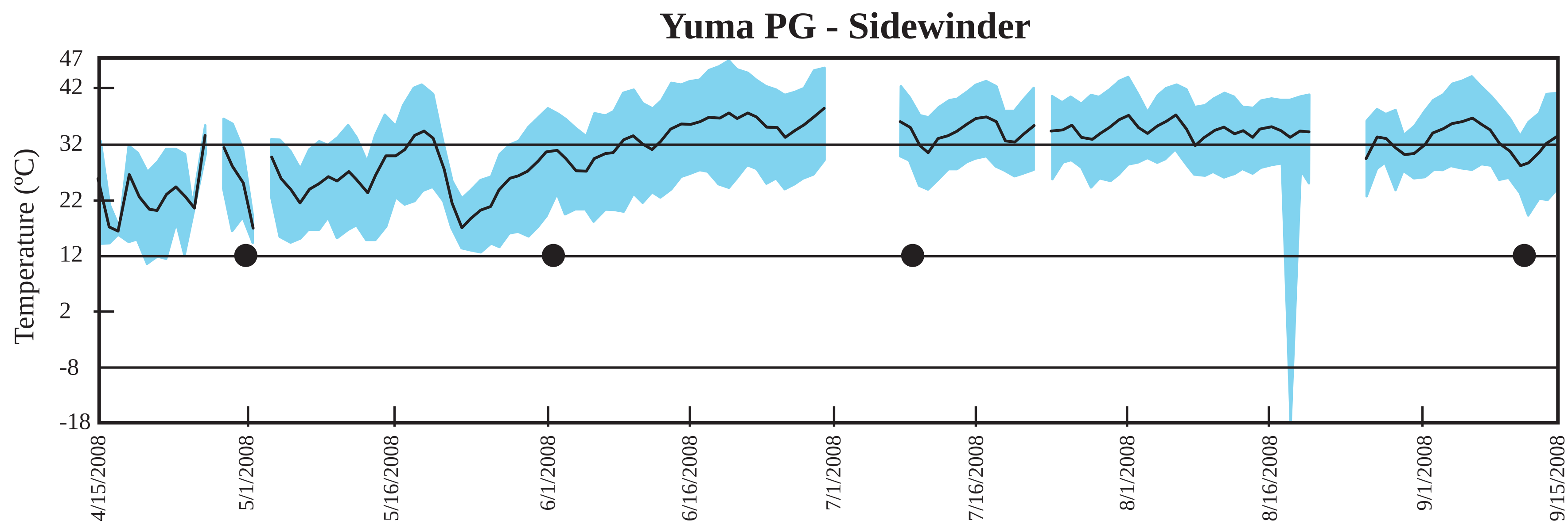
Station: Yuma PG - Kofa Dust

Elevation: 377 ft
Element: Mean Wind Speed

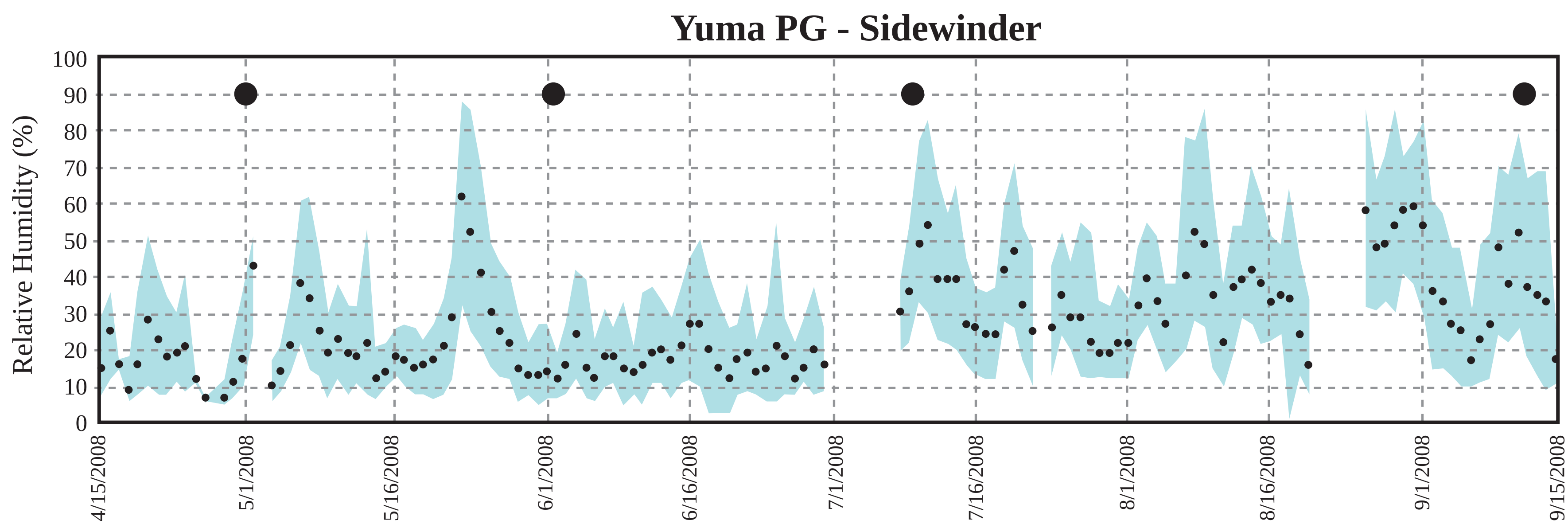


Start Date: 4/15/2008
End Date: 9/15/2008
No. of Days: 154 of 154
No. obs:poss: 9,851 of 14,784

Desert Research Institute	**U.S. ARMY YUMA PROVING GROUND** **DUST SUPPRESSANT TESTING** **Muggins Mesa Dust Course Proxy Wind Rose**	DATE: 2-2-09 FIGURE A-3



Daily Temperature (Average, Maximum and Minimum)



Daily Humidity (Average, Maximum and Minimum)

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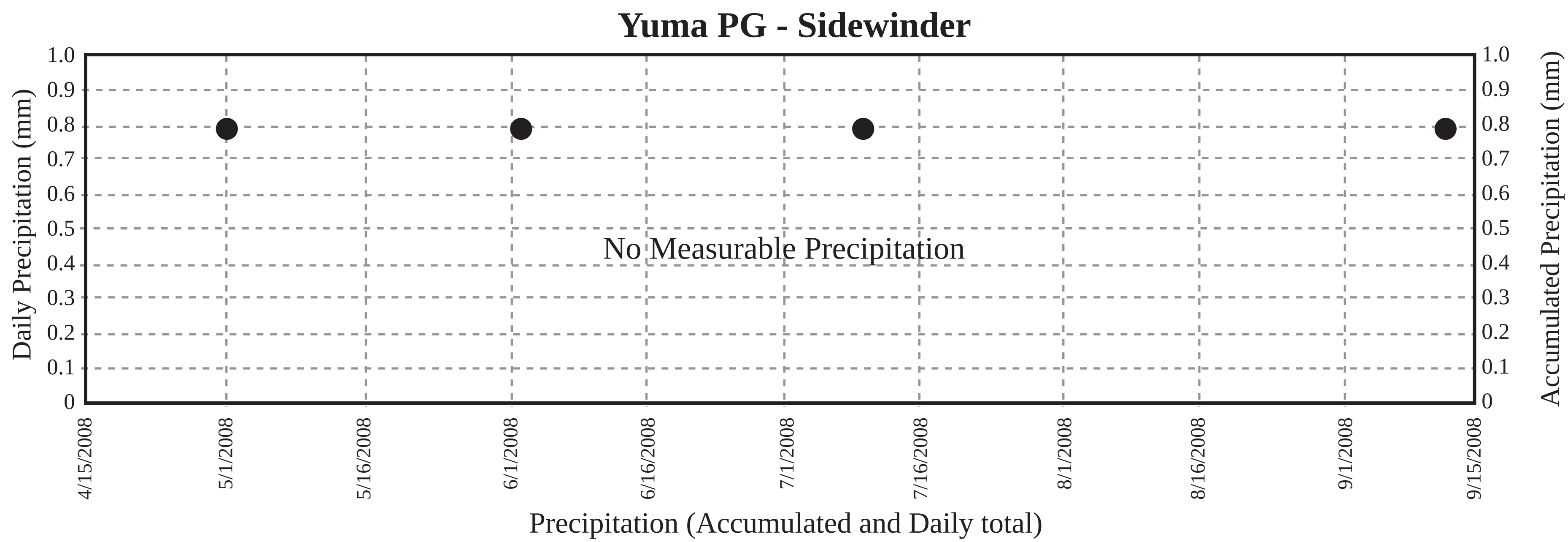
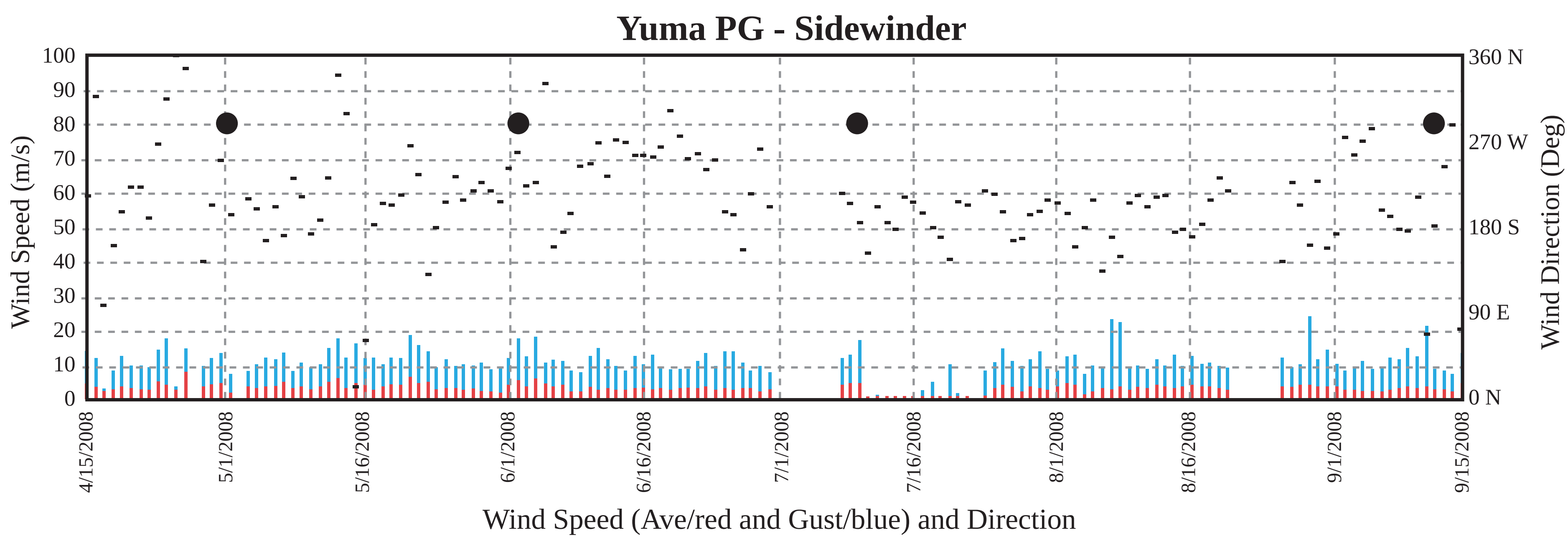
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Proxy Temperature and Humidity

DATE: 2-2-09

FIGURE A-4





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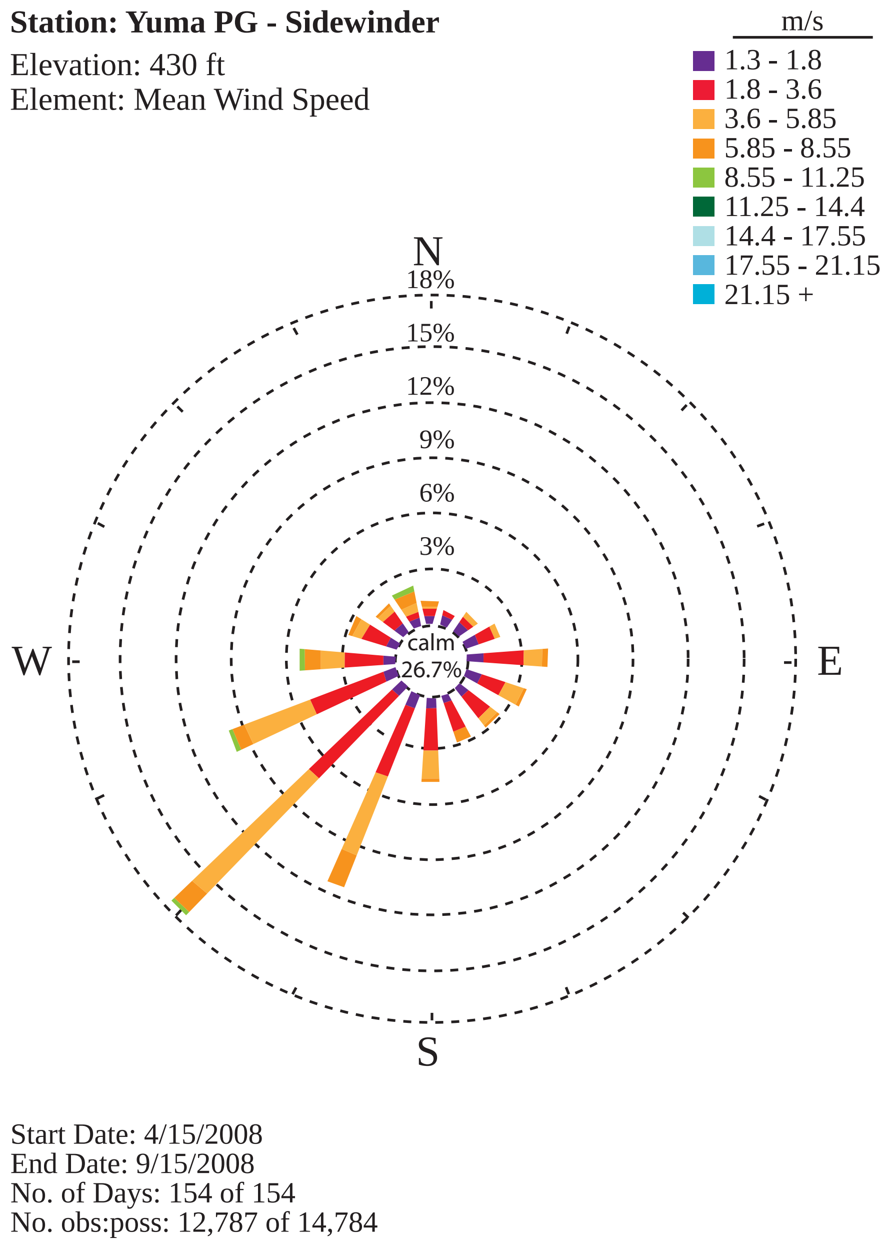
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Proxy Precipitation and Wind Speed

DATE: 2-2-09

FIGURE A-5



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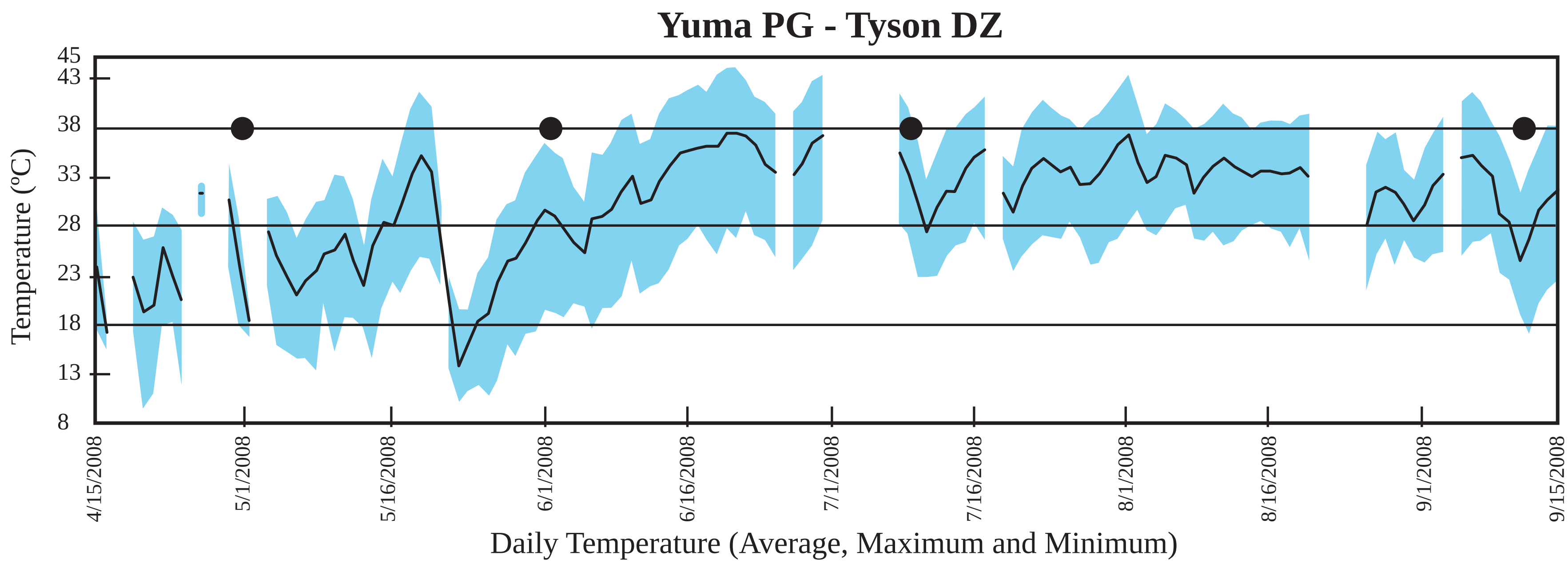
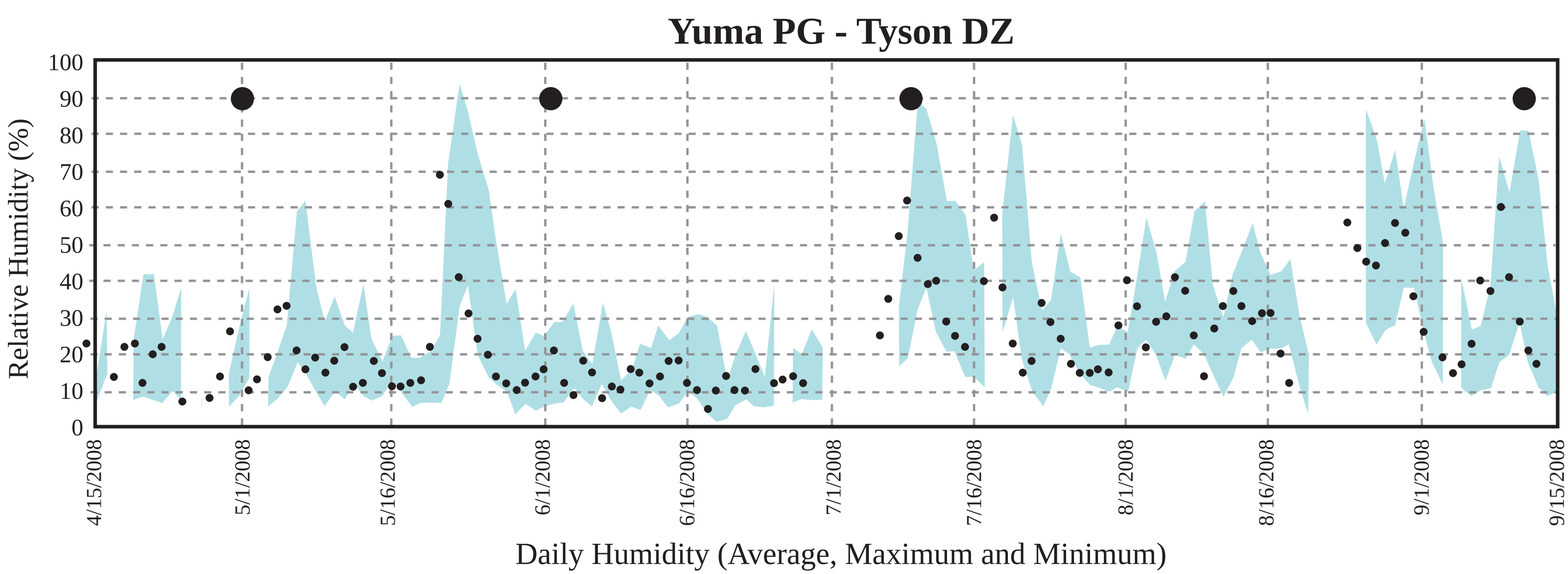
U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Sidewinder Drop Zone Proxy Wind Rose

DATE: 2-2-09

FIGURE A-6





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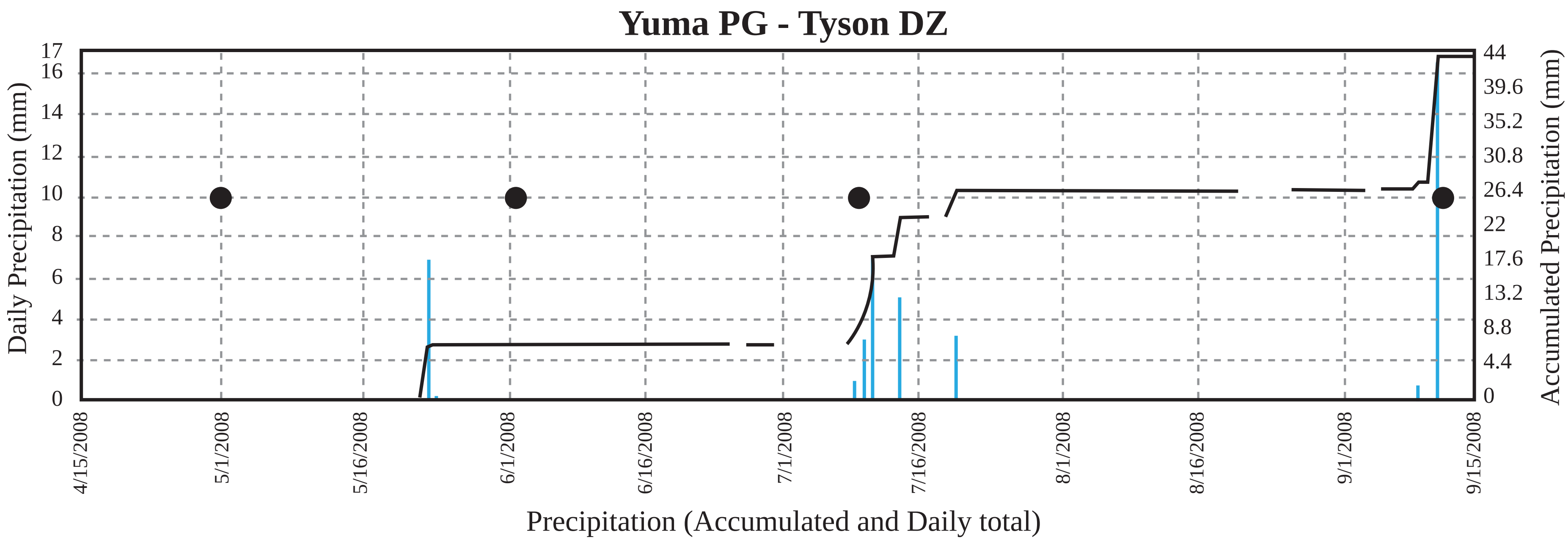
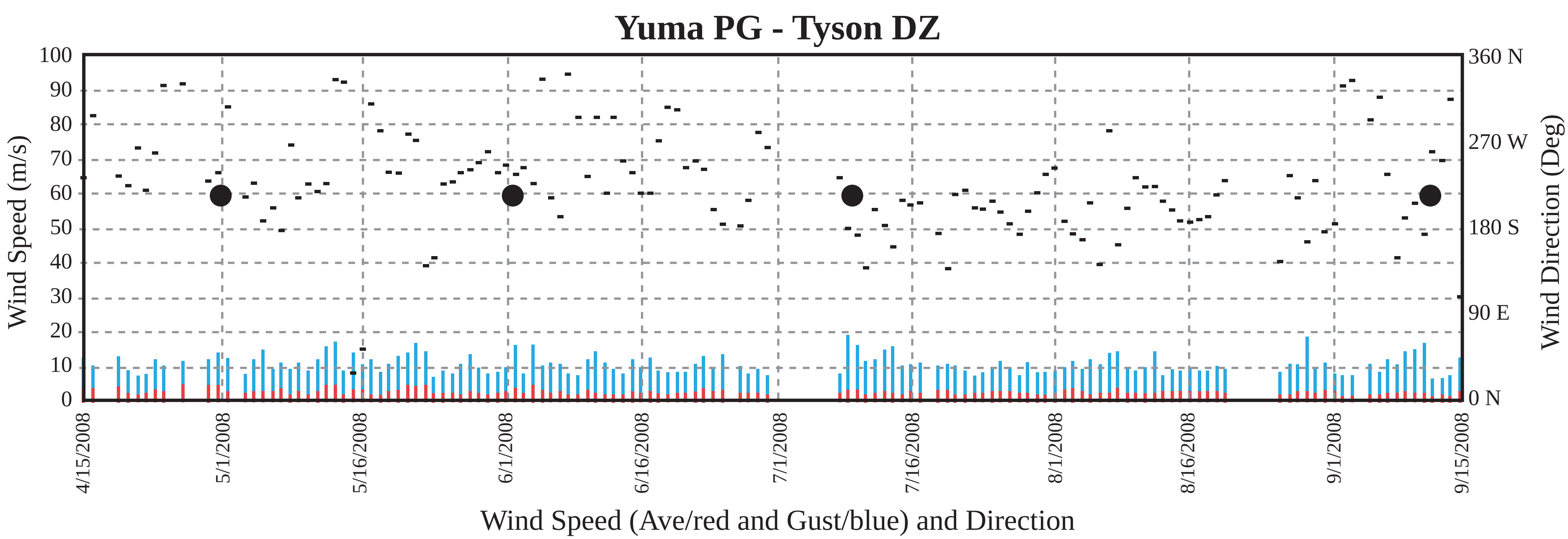
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone Proxy Temperature and Humidity

DATE: 2-2-09

FIGURE A-7





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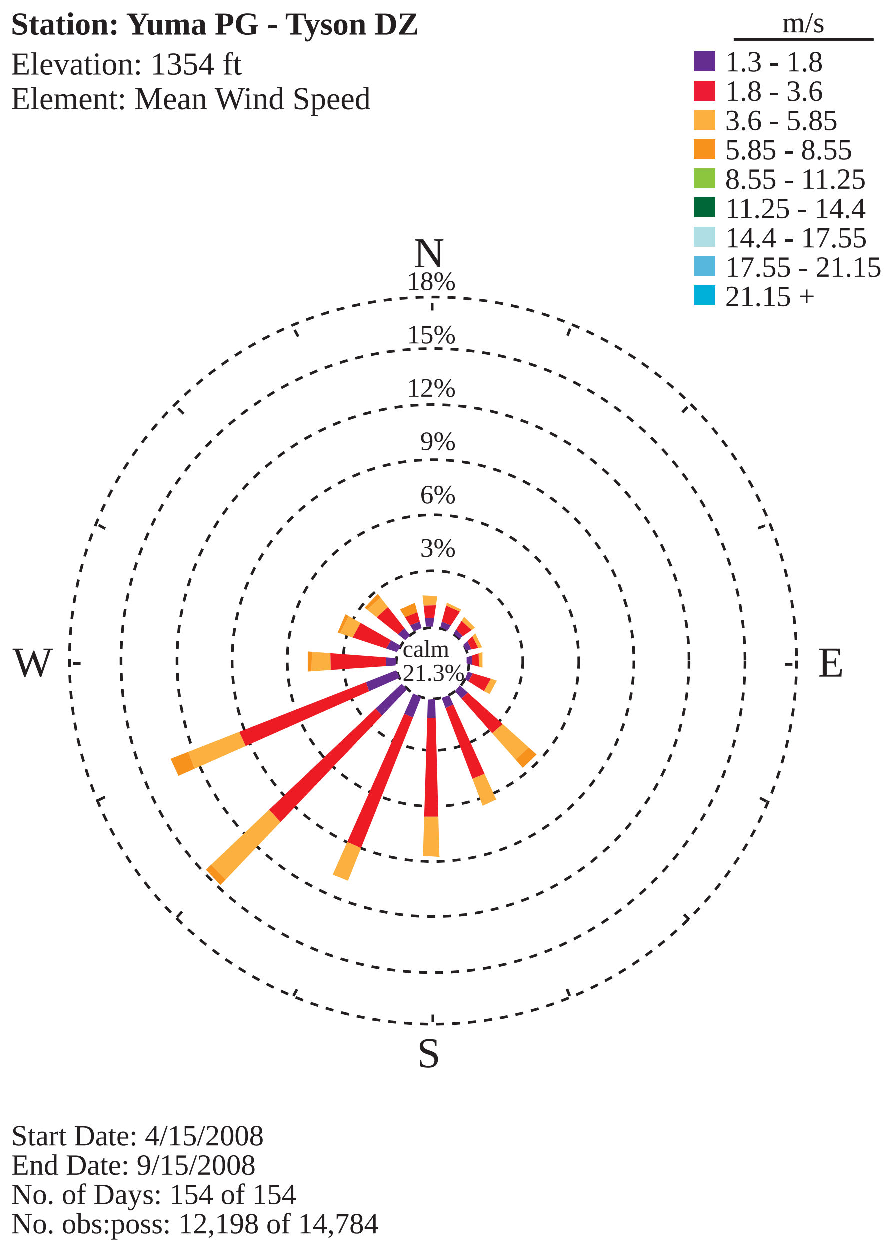
U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
La Posa Drop Zone Proxy Precipitation and Wind Speed

DATE: 2-2-09

FIGURE A-8

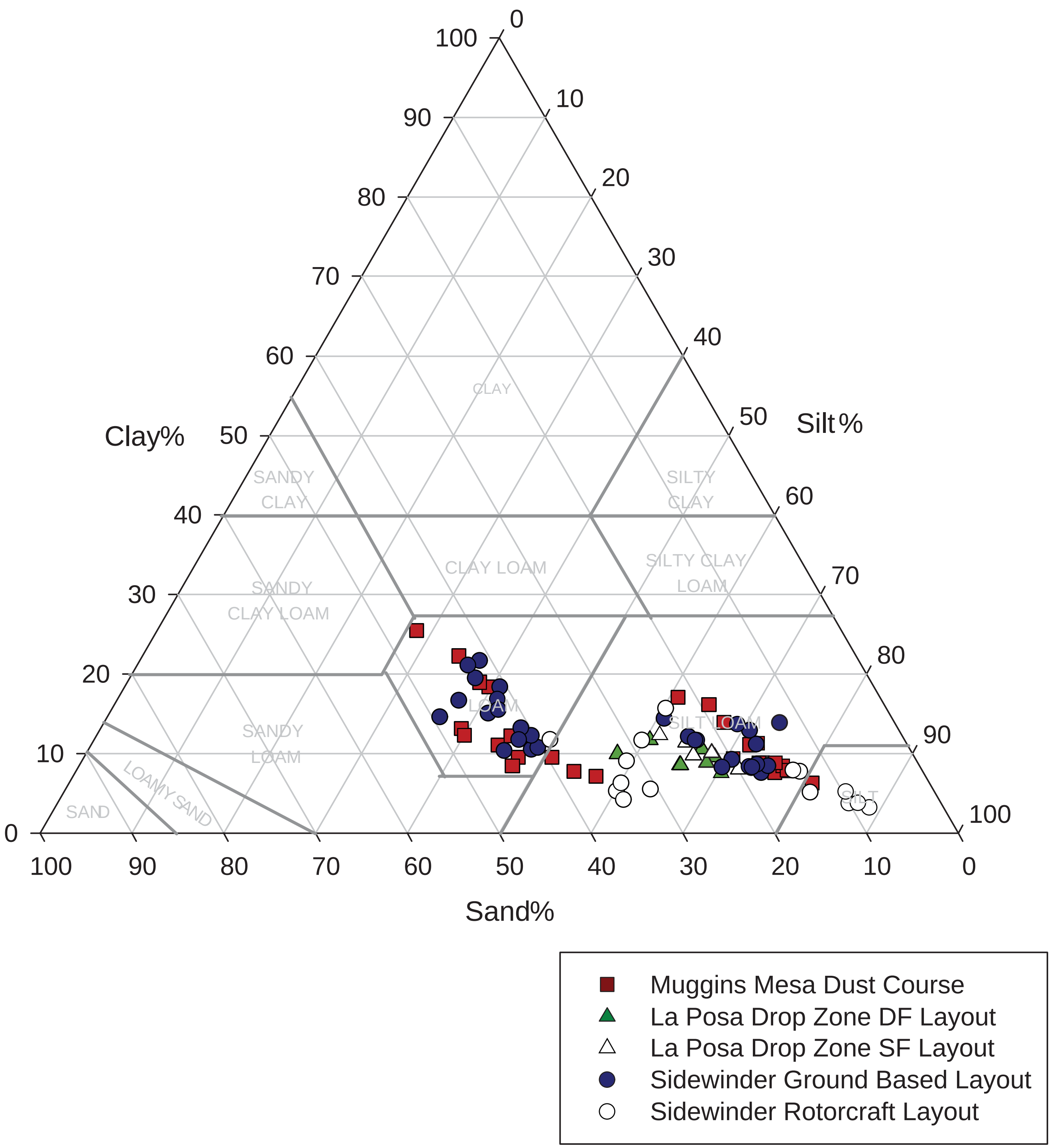


U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
La Posa Drop Zone Proxy Wind Rose

DATE: 2-2-09

FIGURE A-9

9.0 APPENDIX C – SOIL ANALYSIS GRAPHICS



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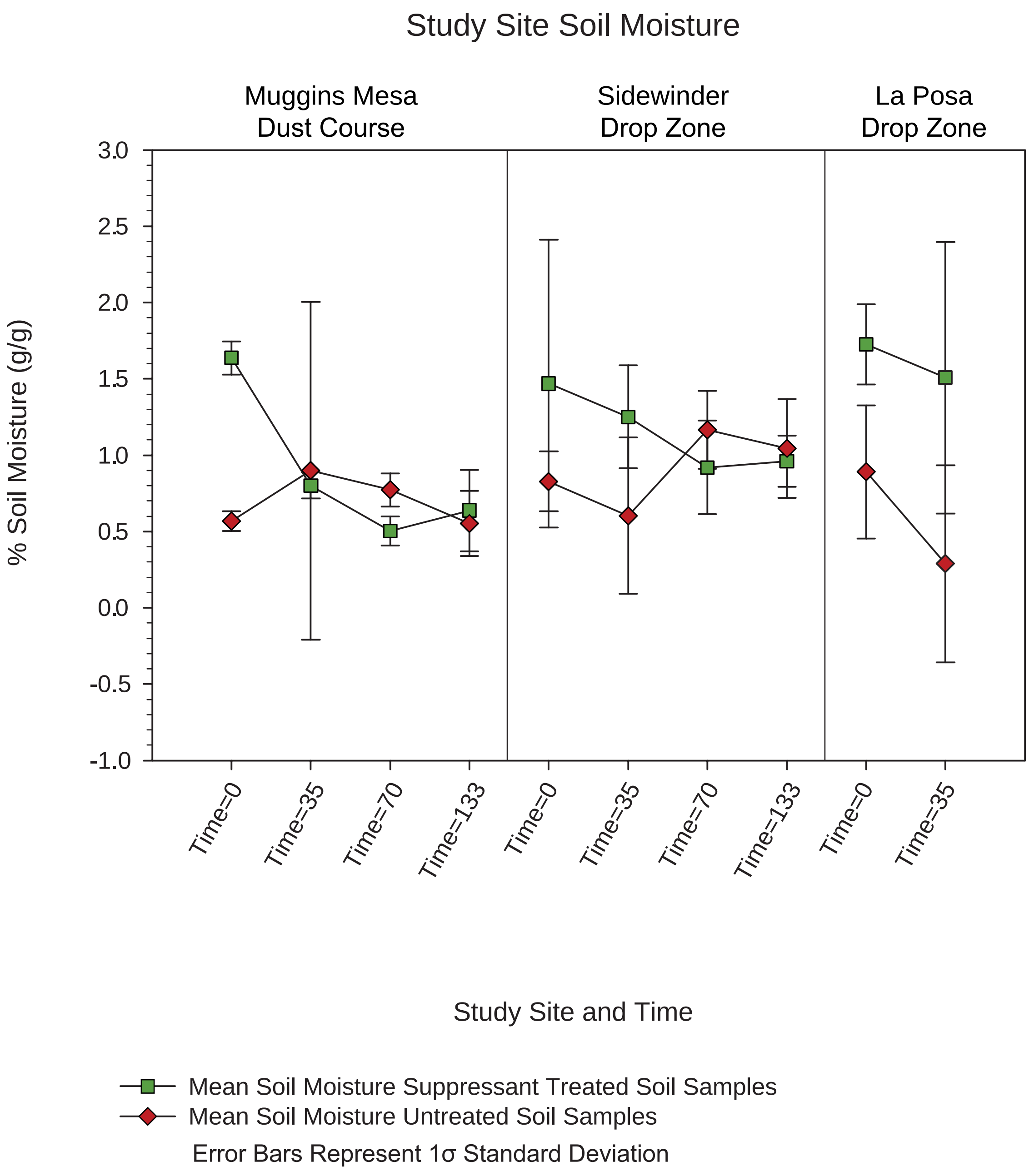
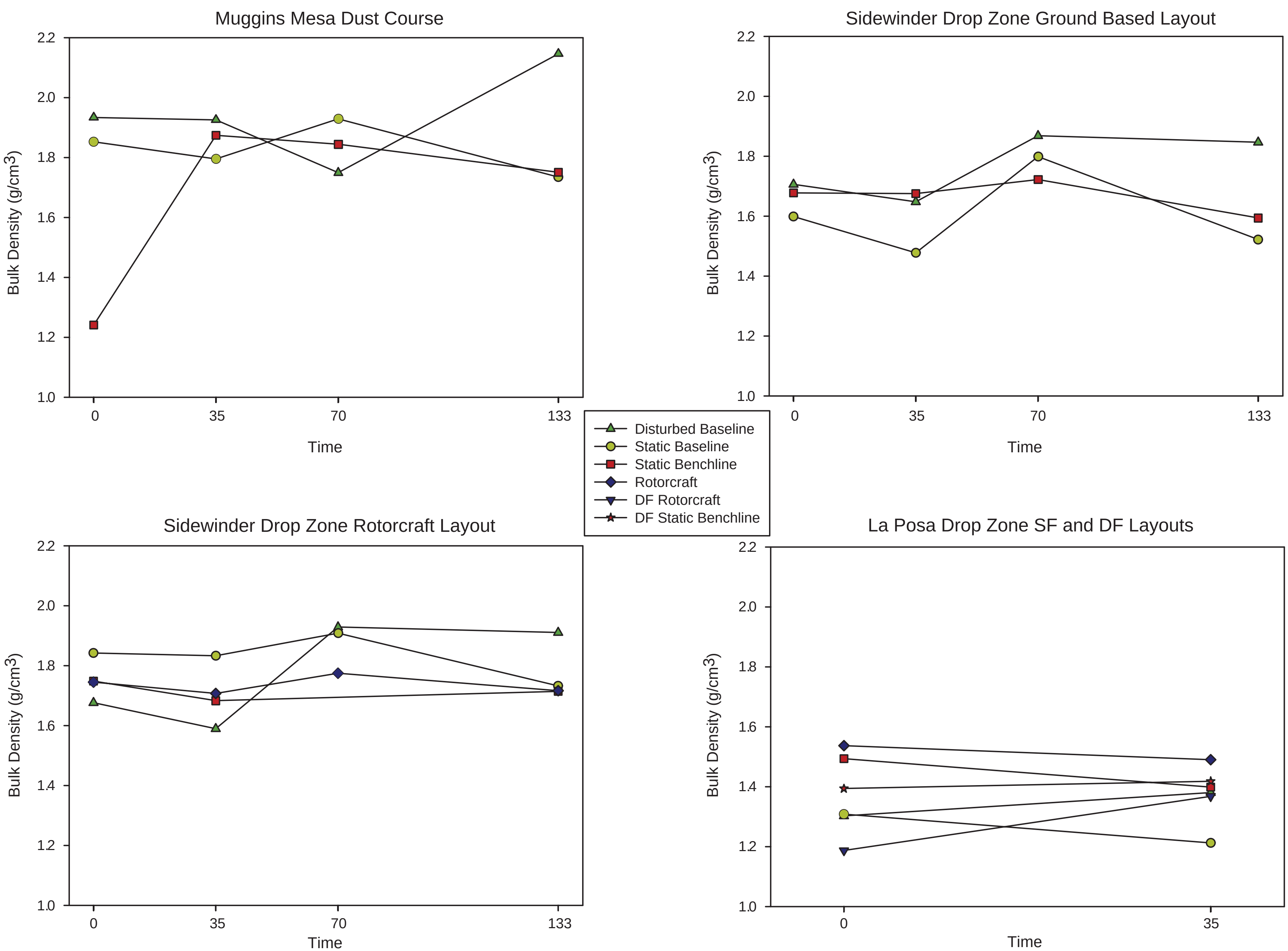
U.S. ARMY YUMA PROVING GROUND
DUST SUPPRESSANT TESTING
Test Layout Soil Texture

DATE: 02-10-09

FIGURE B-1



Desert Research Institute	**U.S. ARMY YUMA PROVING GROUND** **DUST SUPPRESSANT TESTING** **Study Site Soil Moisture**	DATE: 02-10-09 FIGURE B-2



U.S. ARMY YUMA PROVING GROUND - DUST SUPPRESSANT TESTING
Study Site and Test Layout Bulk Density

DATE: 3-9-09

FIGURE B-3

10.0 APPENDIX D – DIGITAL FILES OF SURFACE STRENGTH AND PM10 EMISSION RAW DATA (ON ENCLOSED CD)

11.0 APPENDIX E – DIGITAL FILES OF FIELD FORMS AND PHOTOGRAPHS (ON ENCLOSED CD)